

Continuous Updating of Visuospatial Memory in Superior Colliculus during Slow Eye Movements

Highlights

- Visual neurons in monkey SC retain target location during pursuit eye movements
- These responses are continuously updated in gaze-centered coordinates
- This response is modulated by attention and/or target selection

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In Brief

Dash et al. describe how the monkey superior colliculus keeps track of remembered saccade targets when the eyes follow another moving stimulus. Visual neurons become active when the remembered target crosses their eye-fixed receptive fields, signifying a “moving hill” of memory-related activity, continuously updated in retinotopic space.

Continuous Updating of Visuospatial Memory in Superior Colliculus during Slow Eye Movements

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Summary

Background: Primates can remember and spatially update the visual direction of previously viewed objects during various types of self-motion. It is known that the brain “remaps” visual memory traces relative to gaze just before and after, but not during, discrete gaze shifts called saccades. However, it is not known how visual memory is updated during slow, continuous motion of the eyes.

Results: Here, we recorded the midbrain superior colliculus (SC) of two rhesus monkeys that were trained to spatially update the location of a saccade target across an intervening smooth pursuit (SP) eye movement. Saccade target location was varied across trials so that it passed through the neuron’s receptive field at different points of the SP trajectory. Nearly all (99% of) visual responsive neurons, but no motor neurons, showed a transient memory response that continuously updated the saccade goal during SP. These responses were gaze centered (i.e., shifting across the SC’s retinotopic map in opposition to gaze). Furthermore, this response was strongly enhanced by attention and/or saccade target selection.

Conclusions: This is the first demonstration of continuous updating of visual memory responses during eye motion. We expect that this would generalize to other visuomotor structures when gaze shifts in a continuous, unpredictable fashion.

Introduction

Spatial updating is the brain’s ability to retain spatially accurate information when one moves a sensory organ relative to the physical world [1–6]. In visual and visuomotor systems, this process appears to be largely gaze centered, i.e., relative to the line of sight. For example, the midbrain superior colliculus (SC) possesses retina-like maps of visual space and saccade (rapid eye movement) motor commands that are updated after each intervening saccade [7–9]. Similar mechanisms are thought to be used for other systems, such as reach [10–12].

The time course of transsaccadic updating is hard to study because saccades are rapid and cause widespread suppression of visual signals [13, 14]. Overall, transsaccadic updating

resembles a discrete jump of activity from one set of neurons to another. For example, many saccade-related neurons in the SC and cerebral cortex show predictive remapping: increased activity before and during saccades that bring visual stimuli into their receptive fields (RFs) [15–19]. This predictive activity has been described as a transient extension of the neuron’s RF [15], and could also represent the initial transfer of gaze-centered activity from one population of neurons at the viewing eye position to the appropriate population of neurons for the final eye position [20]. Consistent with the latter view, most parietal eye field neurons either continue or begin to discharge for a remembered visual target after a saccade has brought it into their normal RF, although usually at a much lower rate [15]. Equally important for daily life are the neural mechanisms for visuospatial retention and updating during slow changes in visual direction, e.g., during walking, driving, or smooth pursuit (SP) eye movements. This has also been modeled in gaze-centered coordinates [21–23], but surprisingly, never directly tested. There is reason to suspect that slow updating might differ from transsaccadic updating, because (unlike saccades) slow changes in visual direction (1) do *not* suppress visual input; (2) usually *outlast* delays in visual processing; and (3) have *unpredictable* directions, amplitudes, and durations. Thus, they call for continuous, rather than predictive monitoring. Within a retinotopically organized structure such as the SC [24], this kind of updating would require the continuous motion of a neural population “hill” of activity, in opposition to eye motion (Figure 1) [21–23]. This schema predicts that individual neurons will become active when the remembered stimulus crosses their RF. In the current study we directly tested the predictions in Figure 1 by recording SC neurons while monkeys updated saccade target locations across SP eye movements.

Results

Two female rhesus monkeys (S and W), *Macaca mulatta*, were trained to hold a spatial location in memory (memory target) and make a saccade toward it after an intervening SP (Figure 2A; SP updating task). A typical trial started with the monkey aligning its line of sight to a target placed 10° right, up, or down of straight-ahead position. While fixating, a memory target appeared for 200 ms and the animal kept fixating for another 300–500 ms after which the fixation point started to move and the monkey followed the target with SP. Disappearance of the pursuit target was the “GO” signal for the monkey to make a saccade toward the remembered location of the target. Animals were only rewarded if the saccade landed within 5° (radius) of the remembered target. The paradigm featured four different SP ramp lengths and three to five memory targets per ramp length, randomly interleaved across all trials to ensure that animals could not anticipate final SP position or plan their final saccade before the GO signal (for details, see Supplemental Information available online). When training yielded consistently good behavioral performance (>90% saccades landed within the acceptable tolerance window), animals were prepared for chronic neurophysiological recordings.

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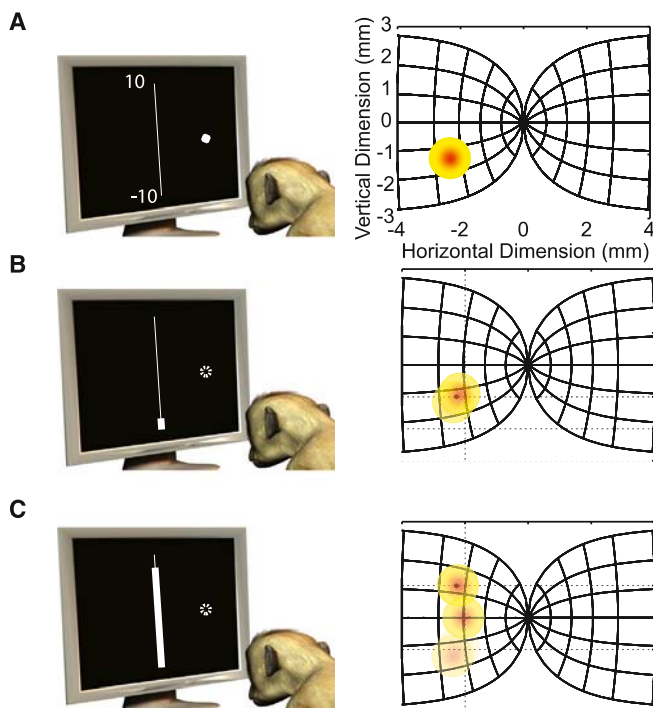


Figure 1. Schematic Prediction of Continuously Updating “Hill” of SC Population Activity for a Remembered Saccade Target during an SP Movement. In order to maintain correct spatial correspondence with the external world, the population activity in retinotopic maps must be updated in opposition to motion of the eye. Here, the left panels show the trial configuration and behavior, and the right panels represent population activity in the SC map, as predicted from its known topography [25–27] and models that utilize continuous eye position or velocity feedback [21–23] to drive spatial updating.

(A) Initial fixation at $0^\circ/10^\circ$ (horizontal/vertical) and presentation of memory saccade target at $10^\circ/10^\circ$ (relative to fixation point) (left). The visual population response corresponding to $10^\circ/10^\circ$ appears with the presentation of memory saccade target (right).

(B and C) Pursuit starts and two snapshots of instantaneous eye positions during and the corresponding population activity on the SC map [25]. Left panel shows instantaneous eye position (white solid line) and their changing spatial orientation with the memory target (red dotted line) when eye had traversed 2° (B) and 18° (C). The right panel shows the corresponding population response traversing the SC map representing the population activity of neurons at $10^\circ/8^\circ$ and $10^\circ/-8^\circ$ (horizontal/vertical; in gaze-centered coordinate frame). The history of moving population activity across the trial is retained (with decreasing contrast) to illustrate the path of the “moving hill” across the SC map.

The Updating Response

We recorded 136 neurons from the putative superficial and intermediate layers of left SC (see methods). Neurons were first classified as visual, visuomotor, or motor neurons using a memory saccade paradigm (see Supplemental Information). Figure 2 shows typical results of a visual-only neuron (no response during saccade). Figure 2B (left) shows the visual RF, with its approximate center indicated by the arrow. Figure 2C shows the task-relevant one-dimensional slice recorded within and beyond the 2D RF shown in Figure 2B, i.e., responses to an array of nine targets corresponding to the spatial range of remembered targets that will pass through the neuron’s RF during our SP updating task (assuming for the moment that this RF is fixed relative to the eye). There was no saccade-related response in this range (gray line), but the visual response (black line) showed a clear peak for the target

placed 4° right and 5° up relative to the fovea. The question here is whether such neurons show a similar response when SP brings a *remembered* saccade target into the same RF position relative to gaze.

Figure 2D shows 2D eye position trajectories (upper panel) and the corresponding neural discharge (lower panel), for the same neuron during our SP updating task. Eye position traces (plotted in four different colors for four different set of trials presented randomly interleaved) followed a consistent 24° leftward SP ramp, but with saccade memory targets placed at four different positions (circles with corresponding colors; not visible during SP). In a given trial only single saccade memory target was shown, i.e., the monkey only had to remember one spatial target. The corresponding neural activity is plotted as a function of horizontal eye position in the lower panel. The color-coded arrows (\downarrow) indicate the estimated eye positions where the remembered target corresponds to the peak of the neurons gaze-centered visual RF (from Figures 2B and 2C).

This visual neuron showed a clear increase in discharge rate when SP brought the location of the memory target into the visual RF, in each case peaking near the peak predicted by the standard RF measurement. Qualitatively, this is exactly the type of spatiotemporal pattern expected if the saccade target location were internally updated relative to gaze, in a direction and speed opposite to that of the SP ramp. In contrast, neural responses corresponding to the end of the pursuit ramp and saccade execution were negligible (Figure 2D, lower panel). These responses were only measured after the original stimulus phosphor had decayed below measurable levels (see Figure S1A and Supplemental Information), persisted for as long as we could measure (1.5–2 s), and often (as shown in Figure 2) showed little or no decrement over time (also see Figures S1B and S1C). Thus, they could only be produced by a mechanism that involves the active retention and updating of the signal.

To objectively evaluate the number of neurons that showed this updating response, we aligned neural activity on the time point when the memory target entered each neuron’s RF. The updating response was quantified using the average neural activity over the following 1 s period (inRF) compared with the preceding 1 s period (outsideRF). Quantified this way, the majority of the recorded SC neurons (126 of 136 neurons) exhibited a statistically significant updating response (Wilcoxon signed rank test; $p < 0.05$). Henceforth, we refer to these 126 cells as “updating neurons.”

In every updating neuron that we examined, the updating response rose, peaked, and fell continuously, depending on the relative locations of the memory target and instantaneous eye position (as in example in Figure 2D). This suggests the response was continuously updated in gaze-centered coordinates throughout the SP ramp. (This cannot be a general response to retinal slip of background motion during pursuit eye movement, because it was spatiotemporally locked to the location of the remembered target.) To confirm this quantitatively across neurons, we aligned the activity corresponding to each memory target (four different colors in Figure 2A) on the time point when the eye position and memory target corresponded with the entry point of the RF and plotted the activity as time continuous spike density profiles (Figure 3A). We then cross-correlated the average spike density profile for the first two memory targets (black and red profiles) to obtain an “updating coefficient.” For example, the neuron illustrated in Figure 2 showed an updating coefficient of $r = 0.95$ (Figure 3A). The median updating coefficient across our 126 updating neurons was 0.67. The distribution of updating coefficients for

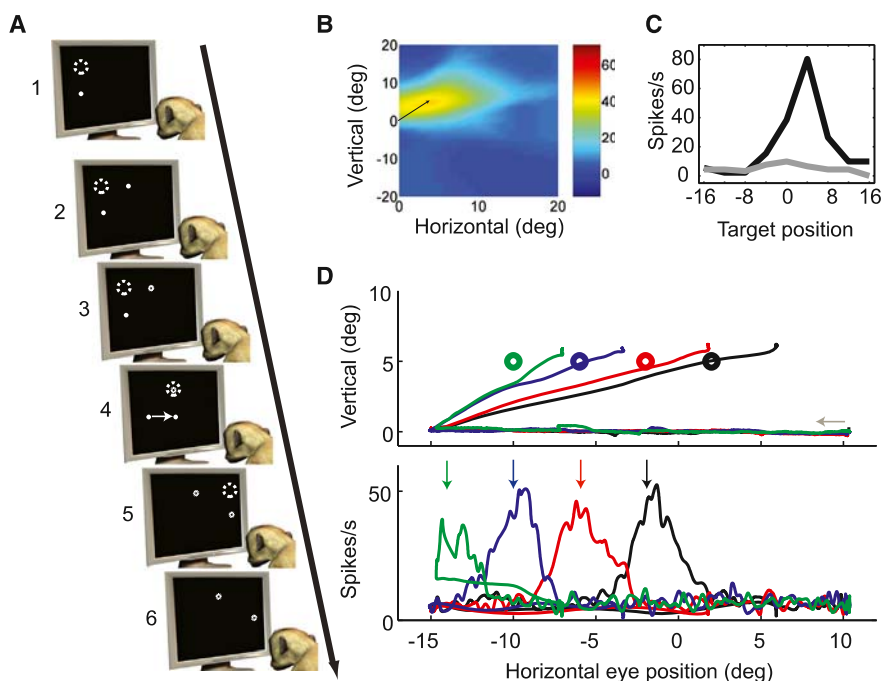


Figure 2. Paradigm and Example Neuron

(A) Sequence of events in a typical trial of SP-saccade updating task. (1) Monkey fixates a white dot on the CRT monitor. The dotted circle indicates RF of a neuron fixed relative to the eye. (2) While fixating, a peripheral target appears for 200 ms and disappears. (3) Animal keeps this location in memory (memory target) and continues to fixate the target for another 300–500 ms. (4) The target starts to move with a constant velocity ($10^\circ/\text{s}$). Monkey follows the target with SP eye movement. The memory target corresponded to RF of the neuron somewhere during the SP. (5) At an unpredictable time during SP the target disappears. (6) At this point the animal is required to make a saccade toward the memory target. The paradigm requires the animal to continuously update its location during the SP. (B) Visual RF of an example visual neuron in 2D spatial coordinates. The color indicates the firing frequency during visual stimulation. This neuron is most active when a visual stimulus was presented rightward and upward in near space (approximate center of the RF indicated with an arrow). (C) Mean firing frequencies corresponding to visual stimulation (black) and saccadic eye movements (gray) for various targets. The choice of these targets depends on the subsequent SP-saccade task.

(D) Eye movement in 2D spatial coordinates (top) and corresponding neural activity (bottom) during the SP-saccade updating task. This is an example of updating across horizontal SP (from 10° rightward toward 15° leftward) followed by a saccade to different memory target (circles; targets were not visible during SP or before the saccade). Colors indicate sets of trials associated with different memory targets. The lower panel shows neural activity as a function of horizontal eye position. The color-coded arrows (\downarrow) indicate the estimated eye positions where the remembered target corresponds to the peak of the neurons gaze-centered visual RF. The strength of the updating response remained robust for the different memory targets without any sign of decay, although different memory targets corresponded with neurons RF at different time points, suggesting an active maintenance of updating response over time.

these cells is illustrated in Figure 3B. These correlations were significantly higher than those computed (as a control) when both response profiles were aligned on the entry point of the RF of the first target (Wilcoxon signed rank test; $p < 0.05$) (also see Figure S4).

Relationship to Visual, Motor, and Memory Signals during Fixation

Next, we asked whether this updating response depended on the category of the neuron: visual response only, visual and motor responses (visuomotor), or motor response only, as classified from our standard memory delay paradigm. Divided this way, 63 of 63 (100%) visual neurons (e.g., Figure 2) and 63 of 64 (98.43%) visuomotor neurons (e.g., Figure S2) exhibited significant updating, but none (0%) of the 9 motor neurons (e.g., Figure S3) exhibited an updating response.

To quantify the strength of the updating response in each of our cell categories, we plotted activity in the updating period (inRF) as a function of the preceding activity (outsideRF) (Figure 4A). Note that all of the visual neurons and most of the visuomotor neurons showed a positive updating response (above slope = 1), but some visuomotor neurons ($n = 9$; 14%) showed a significant decrease in activity during inRF period, i.e., these showed a suppression that was updated relative to gaze. In contrast, motor neurons simply aligned along the slope = 1, showing no updating. To clarify the distributions of these responses we calculated a normalized updating index (Equation 1 in Experimental Procedures). Visual neurons exhibited a stronger median updating index (Figure 4B) than visuomotor neurons (Figure 4C; also see Figure S2), and motor neurons clustered around zero (Figure 4D; also see Figure S3).

These data suggest that in this task visuospatial memory was updated during the SP movement, and saccade motor commands were only updated at the end of SP (Figure S3).

These data further suggest that the continuous updating response during SP is linked to the visual RFs of visual and visuomotor neurons. To test this conjecture, we asked whether the spatial profile of the updating response was correlated with the visual RF acquired during memory saccade paradigm. We calculated the average activity in a 100 ms window during SP starting from when the relative orientation of the eye and the memory target corresponded to five spatial locations (capturing the spatial extent of updating response) and plotted it against the average visual response evoked for the same five spatial locations during memory saccade paradigm. Figure 5A shows the updating response (in a 100 ms period locked to each one of five spatial locations) as a function of visual response for the corresponding spatial locations of the example neuron shown in Figure 2. The spatial response profile of updating and visual response in the example neuron exhibited high correlation ($r = 0.97$).

We did the same analysis on the rest of 125 updating neurons and found a high correlation (median r value = 0.8216; Figure 5B). Visual (median r value = 0.8837) and visuomotor (median r value = 0.8097) neurons exhibited high correlations separately as well. Fifty-one of the 126 updating neurons showed a significant linear relationship, and all of these exhibited an r value >0.95 (mean slope = 0.37). Twenty-four of these were visual neurons and 27 of these were visuomotor neurons. These correlations might have been higher with a larger RF sample and some way to account for the influence of eye motion on RF characteristics. However, our analysis

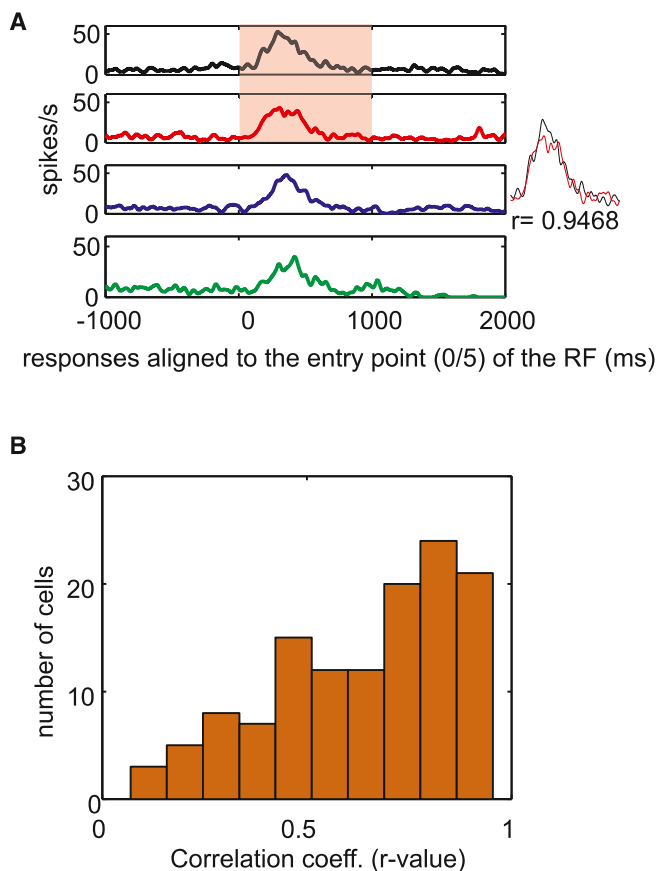


Figure 3. Continuous Updating of Visual Memory

(A) Responses of the example neuron shown in Figure 2, plotted against time (in milliseconds), and aligned to the point in time (0) when eye movement caused the remembered target location to enter the visual RF of the neuron. The response profiles across different conditions are very similar as indicated by the cross-correlation of response profiles of first two panels (corresponding to first two memory targets), with $r = 0.95$. A period of 1 s after entry into the RF was used for cross-correlation.

(B) Cross-correlation of response profiles corresponding to first two memory targets for every neuron showing a significant updating response when the relative alignment of the eye position and memory target corresponded to the entry point of the RF. The median updating coefficient (r) for the entire population of neurons was 0.6979.

confirms that during the SP ramp, a large proportion (51/126) of our cells behaved as if a virtual stimulus were passing through their visual RF.

Thus, the activity we observed in visuomotor neurons cannot be accounted for as general buildup activity, because of its tight spatiotemporal link to the entrance and exit of the remembered target to and from the neurons' visual RFs (Figure S2; Figure 5B). For the same reasons, the updating response cannot be held as a generalized memory response even though a small minority of neurons in our sample did exhibit increased ($n = 12$) or decreased ($n = 9$) activity in the memory interval of memory-guided saccade task. Hypothetically, the updating response in our motor cells could have been missed if the planned memory saccades were very inaccurate [28, 29], especially if overshooting and undershooting orthogonal to the pursuit ramp caused the saccade to go outside of the cell's motor response fields. However, our animals were trained to make saccades within 5° of the target, at the end of four different ramp lengths (Figure S3B). Since

5° is much smaller than the diameter of our neurons' movement fields ($15\text{--}20^\circ$) (Figures S2 and S3), the pursuit ramp had to carry the saccade vector across some part of these cell's response fields, and yet they only fired a burst when an actual saccade was made (Figure S3B). This confirms that our motor responses were only updated at the end of the pursuit ramp, as observed in previous SC studies that looked at transsaccadic updating of motor commands [9].

Topography and Population Response

Figure 6A illustrates the RF hot spot coordinates of our updating neurons, as plotted in the SC map coordinates [25, 30]. As illustrated, we obtained a wide sample $5^\circ\text{--}20^\circ$ amplitude relative to the fovea in all directions, cutting a swath through all directions from up to down. Figure 6B shows the ratio (gain) of the updating response (from our main paradigm) relative the visual response (from our memory delay paradigm), plotted it as a function of spatial distance from fovea (Figure 6B). This plot makes two important points. First, the gain of the updating response varied widely from neuron to neuron. For some neurons the gain is >1 (i.e., the memory response was stronger than the visual response), whereas for other neurons it is close to zero. But on average is about 0.5, similar to the gain of previously observed postsaccadic memory responses [15]. Second, there was no relation between the updating "gain" and the RF hot spot's spatial distance from fovea, i.e., visual and visuomotor neurons updated equally well through the SC map. These data satisfy the assumptions underlying Figure 1.

Influence of Target Selection and Attention on Updating Response

Finally, we asked whether the visuospatial updating response is passively evoked by the presence of any visual target, or whether the updating response requires that the target be actively attended to or selected for a saccade [31, 32]. To test this hypothesis we modified the SP updating task by presenting two targets (white and orange) presented simultaneously in mirror locations. Animals were trained to update the location of the white target and ignore the orange target. The rest of the task is the same as shown in Figure 2A (Figure 7A).

We tested 46 neurons (28 visual and 18 visuomotor) and compared the updating response between the conditions when the target versus the distracter was in the RF. The example neuron shown in Figure 7B shows a clear and robust updating response when saccade target entered the RF and no response when the distracter entered the RF (Figure 7C). All 46 of the neurons in the population showed a significantly stronger updating response toward target when compared to the distracter (Wilcoxon signed rank test; $p < 0.05$). Twenty-eight of 46 neurons showed no significant updating response for distracter (Wilcoxon signed rank test; $p < 0.05$). The overall updating index was also significantly higher for the target compared to the distracter (Wilcoxon signed rank test; $p < 0.05$) (Figure 7D). In summary, continuous updating in the SC visual memory response was not a passive response, but rather was strongly influenced by target selection.

Discussion

We conclude that (1) the SC visual memory response is continuously updated during SP in gaze-centered coordinates, (2) only visual (not motor) responses showed this continuous updating during pursuit, and (3) this response is task (or attention

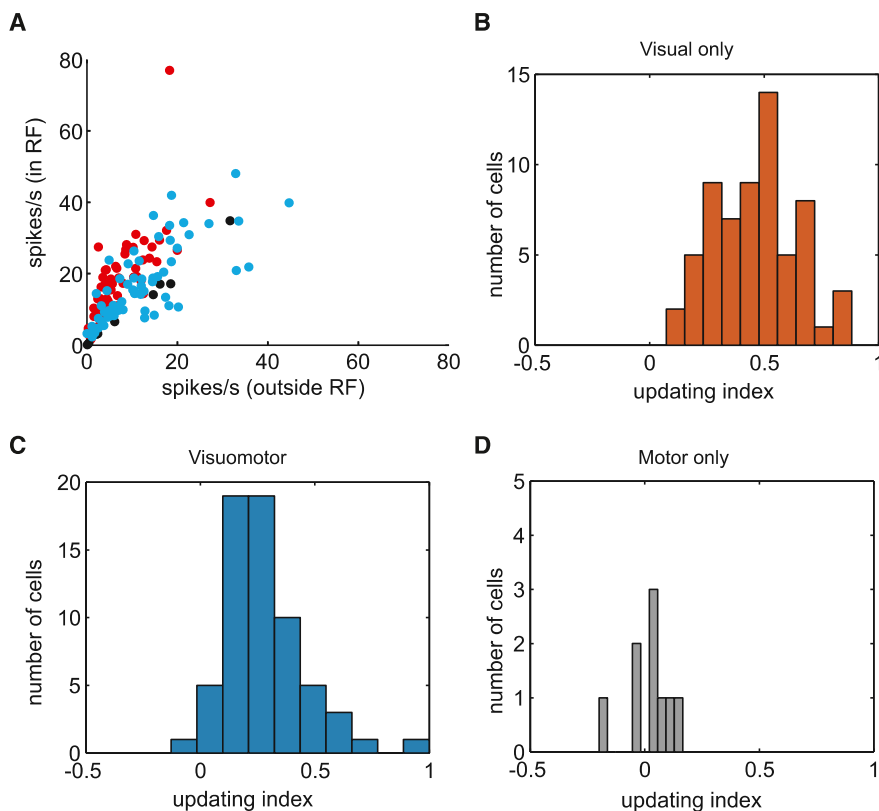


Figure 4. Neuron-Specific Contribution to Continuous Updating

(A) Mean activity of neurons during SP updating when the eye position and memory target position corresponded with the entry point of the neurons RF (inRF) as a function of mean activity during an equivalent period immediately preceding the former (outsideRF). The mean activity for both the periods was sampled for a period of 1 s. Different colors indicate different neuron categories (visual-only neurons [$n = 63$], red; visuomotor neurons [$n = 64$], blue; motor-only neurons [$n = 09$], black). The dots above the diagonal indicate higher firing frequency during inRF period and vice versa.

(B–D) Normalized updating index (Equation 1 in Experimental Procedures) for the population of visual-only (orange) (median = 0.4592) (B), visuomotor (blue) (median = 0.2314) (C), and motor-only (gray) (median = 0.0257) (D) neurons.

updating visual memory and motor preparation [23]. However, these ideas are not mutually exclusive. Finally, the timing and design of the current study do not allow us to calculate whether our updating responses lagged, or were predictive, or maintained in real time.

We cannot directly reproduce topographic populations of activity from our data because we varied the task

and selection) dependent. This shows that the SC is involved in the continuous, active updating of visuospatial memory during slow eye movements. This is the first direct demonstration of gaze-centered spatial updating of visual responses at the single-cell level for any slow tracking movement, and the first study to show gaze-centered updating *during* any type of eye movement.

Our SP-saccade paradigm is most closely analogous to previous double-step studies that looked at updating of signals for a saccade toward a remembered target after an intervening saccade [8, 9, 33]. Some of these studies implicated visual responses in updating, but were unable to follow the spatio-temporal profile of the visual memory trace or demonstrate updating during the first eye movement. Furthermore, the trans-saccadic updating response reported for quasi-visual SC cells [9] was relatively rare, whereas nearly all of our cells with visual responses showed continuous updating SP. It is possible that we missed other visual neurons that are exclusively driven by retinal input [34], but overall this provides a new cognitive role for visual and visuomotor responses in the SC. Based on our data, we believe this role is to briefly monitor the remembered gaze-centered location of a future saccade target and that this activity is only used to reconstruct an updated motor burst vector in visuomotor and motor cells at the time when a saccade is actually planned.

One needs to be cautious in comparing our results to previous studies of predictive remapping during saccades, because these used a single-step paradigm where a visual stimulus was passively presented before a saccade [15–19]. In such tasks, unlike ours, there is no explicit need to retain information or update a motor plan. Thus, the results of those studies have mainly been considered in terms of maintaining perceptual space constancy, whereas we interpret our results in terms of

for each neuron. However, the underlying assumptions behind the schematic model shown in Figure 1 were confirmed by our findings that (1) SC visual memory responses were continuously updated at the single-neuron level and (2) this updating response was equally distributed throughout all points on the SC map from which we were able to record. From this, and the well-known topography of visual responses in the SC [25–27], one can logically infer that SC population activity must update as a hill of activity moving continuously in opposition to SP eye motion. This confirms predictions of models that used eye velocity signals to simulate continuous gaze-centered updating in the SC [21–23], including the presence of a moving hill (Figure 1).

Moving activity hills have previously been proposed for other visuomotor functions, but their existence and role remain controversial. Moving hills corresponding to the error between current and desired gaze position were observed in the cat SC during large gaze shifts [35], but these took the form of a moving wave in the monkey [36]. Thus, our current data provide the first clear evidence for internally generated moving hills in the primate. These moving hills are also reminiscent of the controversial “moving spotlight of attention” theory [37], except that our hills move relative to the eye and are stable in space.

We cannot discount the possibility that eye position affected the responses in our updating neurons because our paradigm was not designed to test this question. But notwithstanding any influence of eye position, every neuron that we recorded with a visual response showed a continuous updating response.

Moreover, although these updating responses were clearly egocentric (i.e., gaze centered), it is possible that they were driven in part by allocentric cues (e.g., the edge of the computer screen or the pursuit target itself), in addition to internal

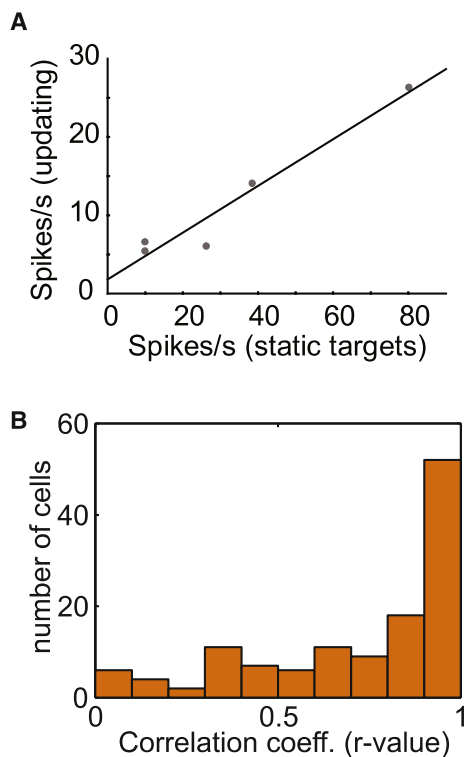


Figure 5. Visual RF versus Updating Response

(A) Updating response during SP updating and visual response during memory saccade paradigm of the example neuron in Figure 2 for five spatial orientations capturing the spatial extent of the updating response. There is a clear linear relationship with a high correlation coefficient ($r = 0.97$).

(B) Correlation between the spatial profile of updating response and visual responses for all the neurons. The median $r = 0.82$.

efference copies of eye motion. Future experiments could test between the signals that drive this response by manipulating the presence or absence of allocentric cues. Finally, we cannot entirely dismiss the possibility that our animals' behavior and neural responses were influenced by additional phosphor persistence, related to the saccade stimulus or otherwise, that could not be detected either by the human eye or by our photodiode. However, it is very unlikely that this alone could account for the robust and sustained memory responses that are reported above.

General Implications

We hypothesize that the continuously updated signals observed in this study are part of a physiological system that has not been studied before; a system that provides continuous access to remembered visual locations during continuous self-motion. If so, this should generalize in several ways that can be tested experimentally. First, this hypothesis predicts that continuous updating signals should also emerge in other visuomotor areas of the brain that have previously been implicated in discrete remapping during saccades, but that have not been tested during behaviors that involve continuous eye motion. Second, the updating observed during SP would also be evoked during other continuous motion behaviors such as walking and driving or general navigation (the signals driving the updating might differ, but the result should be the same). Third, although these signals are presumably used to drive saccades in the current study, in principle they could be used to drive other goal-directed visuomotor behaviors.

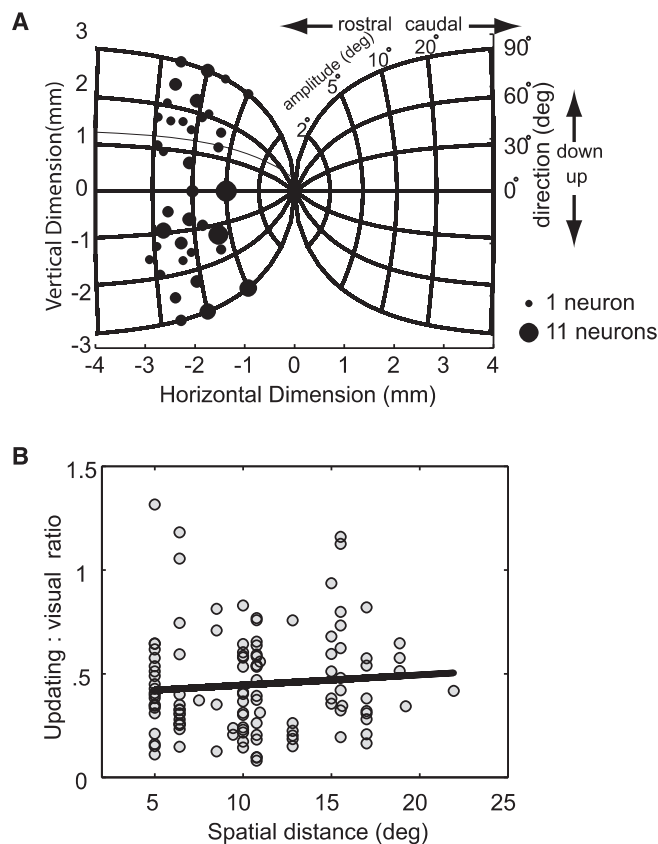


Figure 6. Strength of Updating with Increasing Distance from Fovea

(A) Location of RF hot spots of all the updating neurons in SC map. All the neurons were recorded from left SC of both the animals. See Marino et al. [25] for the algorithm to convert spatial coordinates to SC map. Size of the circles indicates the number of neurons recorded from a particular site. (B) Ratio of updating response and visual response at every neuron's RF hot spot as a function of spatial distance of neuron's RF from fovea. There is no relationship between distance of RF hot spot and strength of updating response ($r^2 = 0.007$, $p = 0.36$).

Experimental Procedures

Surgical Preparation and Electrophysiological Procedures

Two female rhesus monkeys (W and S) were prepared for head immobilization, 2D eye movements recording, and chronic electrophysiological recordings from SC (see Supplemental Information for details). All surgical and experimental procedures were approved by the York University Animal Care Committee and were in compliance with the Canadian Council of Animal Care policy on the use of laboratory animals. After the initial characterization of SC neurons (as visual, visuomotor, or motor neurons) and their visual and motor RFs were specified using a memory saccade paradigm (see Supplemental Information), monkeys were tested with the SP updating task.

Data Analysis

Trial history, eye position records sampled at 1.5625 kHz, and the times of identified spikes were stored for later offline analysis. In addition, high-resolution (25 kHz) records of the electrode signal were kept for later reconsideration of the spike identification obtained online. The analysis was carried out using customized MATLAB programs (MathsWorks). The horizontal and vertical eye position records were smoothed using a Savitzky-Golay filter (window = 20 samples; polynomial degree = 4), which replaces the data points in the specified window by a polynomial fit of chosen order. We estimated the instantaneous firing rate of the recorded neurons with a continuous spike density function, generated by convoluting the spike train with a Gaussian function of $\sigma = 10$ ms width. We converted the discharge into spike density functions in order to obtain the continuous description of neuronal activity.

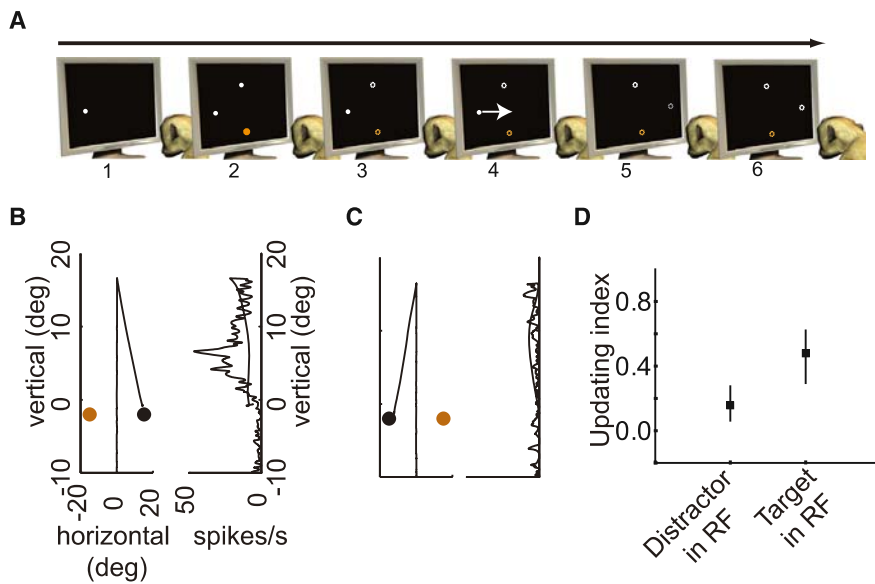


Figure 7. Continuous Updating Requires Active Attention

(A) (1) Monkey fixates a white dot on the CRT monitor for 500–800 ms. (2) While fixating, two peripheral targets (white and orange) appear in mirror symmetric locations for 200 ms and disappear. (3) The animal keeps the location of white target in memory (memory target), ignores the orange target (distractor), and continues to fixate the target for another 300–500 ms. (4) The fixation target starts to move with a constant velocity ($10^\circ/\text{s}$). Monkey follows the target with SP. (5) At an unpredictable time during the SP, the target disappears. (6) At this point, the animal is required to make a saccadic eye movement toward the white memory target.

(B) Eye movement in 2D spatial coordinates (left) and corresponding neural activity (right) during a modified SP updating task. This is an example of updating across vertical SP (from 10° downward toward 15° upward) followed by a saccade to the white memory target (shown in black). The animals were trained to ignore the orange target (distractor). Targets were not visible during SP or before the saccade. The white and the orange

memory target were shown in the contra- and ipsilateral SC, respectively. The right panel shows an increase in neural activity when the eye position during SP and the white memory target corresponded with the neuron's RF.

(C) Eye movement in 2D spatial coordinates (left) and corresponding neural activity (right) (similar to B, except memory targets switched so that white and orange were shown to ipsi- and contralateral SC, respectively). The rightward panel shows no updating response when the eye position during SP and the orange memory target corresponded with the neuron's RF. The axis values in (C) are identical to (B).

(D) Comparison of updating index for the population of neurons ($n = 46$) when the white memory target was in RF (target in RF) and when the orange memory target (distractor) was in the RF. Updating index for white memory target was significantly higher when compared to orange memory target ($p < 0.0005$; Wilcoxon matched pair test). The data are represented in median and interquartile range.

SP Updating Task

The experimental configuration for the updating task was arranged for each SC neuron based on the location of its visual RF as explained earlier. In case of motor-only neurons, the motor map was used to configure the experiment. The neural activity during the SP updating task was plotted in two different ways for convenient visual analysis of the responses. The first representation is shown in Figure 2D, where neural activity is plotted in spatial coordinate during SP. In this example only responses during 24° SP ramp (data from 16° , 20° , and 28° SP ramp not shown) and for four possible memory targets are shown in different colors. Although this representation allowed an easy and comprehensive look at the overall result, but it made it difficult to pool data across different SP ramp lengths. The second representation was based on representing data in time. Data were aligned on eye position when they corresponded with the end of the SP target ramp. Here, the updating response could be observed in time for each of the memory target locations and when the eye position during SP corresponded with the visual RF. For example, the memorized location of the black target corresponded with visual RF of the neuron before that of the red target; therefore, the updating response to the black target appears earlier in time. In this arrangement data from all four SP ramp lengths could be pooled for memory targets whose retinal coordinates were the same relative to SP target ramp end.

The above-mentioned two representations were used for qualitative observation of the neuron's behavior during SP-saccade updating task. To quantitatively study the updating response, data were aligned on the time point when the visual angle subtended by the instantaneous eye position and the memorized target location corresponded to the entry point of the RF. The entry point of the RF was derived from the second block of memory saccade trials that was carried out for seven to nine selected positions in retinal coordinates. The targets for which there was a significant visual response defined the entry point, exit point, and center of visual RF (in one dimension) in the SP updating task. For example, in Figure 2C, significant visual responses were observed for the retinal coordinates $0^\circ/5^\circ$, $4^\circ/5^\circ$, and $8^\circ/5^\circ$ (horizontal/vertical). Therefore, during the SP updating task $0^\circ/5^\circ$ was taken as the entry point of the visual RF as it was the first significant visually responsive retinal coordinate encountered during SP.

The average neural activity during the 1 s period following entry into the RF (inRF) was compared with the immediately preceding 1 s (outsideRF).

If the activity in the inRF was significantly different from outsideRF, the neuron was deemed to be showing an updating response (Wilcoxon signed rank test; $p < 0.05$). To see the difference in strength of updating response across three neuron types in SC, we also calculated a normalized updating index by using the formula

$$\text{Updating index} = (\text{inRF} - \text{outsideRF}) / (\text{inRF} + \text{outsideRF}). \quad (\text{Equation 1})$$

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures and four figures and can be found with this article online at <http://dx.doi.org/10.1016/j.cub.2014.11.064>.

Acknowledgments

This project was funded by the Canadian Institutes for Health Research. J.D.C. was supported by a Canada Research Chair, and S.D. was supported by an Ontario Ministry of Research and Innovation Fellowship. We thank S. Sun for computer programming support and R. Marino and A. Sajad for constructive comments on the study and manuscript.

Received: October 1, 2013

Revised: October 15, 2014

Accepted: November 25, 2014

Published: January 15, 2015

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