LIP represents the visual location of saccade targets.

The lateral intraparietal area (LIP) codes the location of saccade targets and not the dimension of the saccades that will be made to acquire them.

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Abstract

Activity in the lateral intraparietal area (LIP) represents a priority map which can be used to direct attention and guide eye movements. However, it is not known whether this activity represents the location of saccade targets or the actual eye movement made to acquire them. We recorded single neurons from rhesus macaques (*Macaca mulatta*) while they performed memory-guided delayed saccades to characterize the response profiles of LIP cells. We then separated the saccade target from the saccade endpoint using saccadic adaptation, a method that induces a change in the gain of the oculomotor system. We plotted LIP activity for all three epochs of the memory-guided delayed response task (the visual, delay period and presaccadic responses) as a function of target location and saccade endpoint. We found that under saccadic adaptation the response profile for all three epochs was unchanged as a function of target location. We conclude that neurons in LIP reliably represent the locations of saccade targets, not the amplitude of the saccade required to acquire those targets. Although LIP transmits target information to the motor system, that information represents the location of the target and not the amplitude of the saccade that the monkey will make.
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Introduction

Activity in the lateral intraparietal area (LIP) represents a priority map of the visual field (Ipata et al., 2009), which is important in specifying the locus of visual attention (Bisley and Goldberg, 2003a) and choosing targets for saccadic eye movements (Gnadt and Andersen, 1988). The signal in LIP can be entirely dissociated from saccade generation but does convey information about impending eye movements when they are appropriate (Gottlieb et al., 1998, 2009; Gottlieb and Goldberg, 1999; Bisley and Goldberg, 2003b), and under certain circumstances, can predict both the target and reaction time of saccades (Ipata et al., 2006).

However, because in many studies of LIP the target location and the saccade endpoint overlapped in space, it has been difficult to interpret whether activity in LIP represented the location of the saccade targets or the dimensions of the saccade the monkey made to acquire the target. In a study looking at the deviation of saccadic amplitudes from an expected two-dimensional Gaussian distribution, Platt and Glimcher concluded that LIP neurons represent the movement and not the target (Platt and Glimcher, 1998).

Here we sought to distinguish between a sensory and a motor representation by recording the activity of single neurons while dissociating the target location and saccade amplitude, using saccadic adaptation to change the gain of memory-guided delayed and visually-guided saccades (McLaughlin, 1967). Saccadic adaptation is accomplished by repeatedly providing the subject with misleading post-saccadic feedback of the target location, mimicking an error in the oculomotor system. After multiple repetitions (several hundred trials in monkey, ~50 trials in human), the subject makes a saccade not to where the target was when the saccade began, but to where it is after the saccade.

We predicted that if LIP represented the movement, the neural output from cells would reflect the saccade amplitude, regardless of the location of the target. However, if LIP represented the target, the neural output would reflect the visual target location regardless of saccade amplitude. We found that activity in LIP reliably reflects target location throughout the visual, delay and presaccadic epochs of a memory-guided delayed saccade, even when the saccades that are evoked by the target land far from it due to changes in oculomotor gain.
Materials and Methods

Subjects

All of the protocols were approved by the Animal Care and Use Committees at Columbia University and the New York State Psychiatric Institute as complying with the guidelines established in the United States Public Health Service Guide for the Care and Use of Laboratory Animals. Two rhesus monkeys (Macaca mulatta), one female (Monkey B) and one male (Monkey C), both weighing approximately 6 kg, were used in these experiments.

Preliminary training and preparation for physiology.

Monkeys were first trained to sit in a primate chair using a pole and collar technique. After chair training, monkeys were surgically prepared for physiology using sterile surgical techniques, ketamine induction and isofluorane anesthesia. 16-20 titanium screws were implanted in the skull, and bound together with Jet-Dry acrylic. A nylon headholder socket was implanted in the acrylic into which a stainless-steel headpost could be inserted. Scleral search coils were implanted subconjunctivally (Judge et al., 1980), and the coil wires brought subcutaneously to the acrylic implant, where they were connected to a plug. The monkey was allowed to recover fully before testing restarted. During testing, monkeys worked for their daily water intake and were supplemented with dried and fresh fruits. Monkeys’ weights and general health were monitored daily.

Behavioral Methods

Eye movements were monitored using surgically implanted scleral search coils sampled at 1 kHz, and decoded using a Northmore phase detector (Crist Instruments). During testing, monkeys sat in a primate chair with their heads held by a post affixed to the chair, in a dark, sound-attenuated Faraday room. The monkeys sat 57 cm away from a CRT monitor (ViewSonic Professional Series P225F) with a refresh rate of 120 Hz. In all experiments, the fixation point and saccade targets each measured 0.2° of visual angle and were displayed on a black background. The monkeys were trained on three standard tasks: fixation, visually-guided saccades, and memory-guided saccades. Each task began with the appearance on the screen of a 0.2° fixation point. In the fixation task, the monkey had to acquire the fixation point within a window of 3°, and fixate for 3-4 s, during which time task-irrelevant visual stimuli identical to the fixation point were flashed at pseudorandomly chosen points on a 40°x40° grid, for 50 ms, with a 500 ms interstimulus interval. The monkey received a drop of liquid as a reward for...
LIP represents the visual location of saccade targets remaining within the fixation window. In the visually-guided saccade task the fixation point remained on for 450 ms, after which it disappeared and a saccade target appeared elsewhere on the screen. The monkey had to make a saccade to the target within 500 ms, and it was rewarded for fixating the saccade target for 500 ms. In the memory-guided saccade task, the saccade target appeared for 100 ms and then disappeared. The monkey had to maintain fixation for another 600-900 ms, after which the fixation point disappeared and the monkey had to make a saccade to the spatial location of the vanished stimulus. If it did so, the target reappeared and the monkey was rewarded for continuing to fixate it for at least 200 ms.

We used two different saccadic adaptation tasks. In the memory-guided delayed saccade adaptation task (Fig 1a), the monkey fixated for 500 ms, after which a saccade target appeared for 100 ms. After another 600 to 900 ms the fixation point disappeared, and the monkey made a memory-guided saccade to the spatial location of the vanished stimulus. During the pre-adaptation baseline phase, the monkey made accurate saccades (illustrated by a single trial example, Fig 1b; see Fig 2a for the mean and SEM of pre-adaptation saccades in a given experimental day) to the target. During saccadic adaptation, the target reappeared at a point between the original fixation point and the saccade target, so the unadapted saccade was now inaccurate, and the monkey had to make a corrective saccade to acquire the target (illustrated by a single trial example, Fig 1c). During the adaptation phase, the monkeys made increasingly shorter saccades and smaller corrective saccades (Fig 1d). During the post-adaptation phase, monkeys made shorter, adapted saccades directly to the shifted locations, minimizing or eliminating the corrective saccade (Fig 1e). To induce saccadic adaptation in the visually-guided saccade paradigm we blanked the saccade target when the saccade began, and brought it back on at the shifted location after the saccade. This technique takes advantage of saccadic suppression; humans report that they do not perceive the change in stimulus location (Bridgeman et al., 1975), and monkeys behave as if they do not.

To discourage errant eye movements and ensure that the desired vector was adapted, we applied constraints on both the saccade’s horizontal and vertical components. The trial was aborted if the monkey’s initial saccade did not fall within the wedge-shaped area described by a set length and angle based on the vector between the fixation point and the saccade target. If the first saccade did fall within this area, the trial would continue and if the monkey had not already acquired the saccade target, it had the opportunity to do so with a second saccade. The width and
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length of the sector were adjusted proportionally to the eccentricity of the saccade target
locations, that is narrower for long saccades and wider for short saccades, to maximize the
proportion of appropriate saccades. Importantly, because the monkey was rewarded for making
saccades to the spatial location of both the original target and the ultimate saccade target
locations, there was no operant reason for the monkey to change the gain of its saccade — any
adaptation was a natural response to the error of the saccades.

Physiological methods

After basic behavioral training, we used a 2 cm trephine to expose the dura overlying the
intraparietal sulcus (using coordinates determined from a T1 volume MRI measured on a GE 1.5
T Signa Scanner), over which a recording chamber was affixed in monkey B (monkey C already
had a recording chamber). We operationally defined LIP as an area on the posterolateral bank of
the intraparietal sulcus with cells which responded during the memory-guided delayed saccade
task with visual, delay period and presaccadic activity. We controlled all experiments using the
REX system (Hays et al., 1982) and recorded single-unit activity with glass-insulated tungsten
electrodes introduced through a guide tube positioned in a custom-made plastic grid with 1mm
spacing between possible penetrations, using an FHC Neurocraft head stage and amplifier, which
we then passed through a Krohn-Heit Butterworth filter with a band pass > 300Hz and < 3000Hz
in order to eliminate noise from the mains and the coil signal. We used a Dell computer running
the LSR MEX spike sorter on line to generate unit pulses. We only analyzed data from neurons
which we could keep isolated throughout the adaptation session. In general, recording sessions
lasted between 5 and 8 hours depending on the stability of the cell and the monkey’s willingness
to continue to work. We took care to avoid making penetrations with the electrode in adjacent
grid holes from the previous day’s penetration in order to reduce tissue damage. During every
testing and training session, monkeys were monitored using a closed circuit camera and monitor.
Monkeys’ behavior was also described in logs. Stimulus timing was verified using a photoprobe
that measured the actual appearance of stimuli on the screen.

Experimental design

Once we found an LIP cell we used the fixation task to characterize its receptive field,
generating a map of locations that evoked visual responses (measured 50-150 ms after the flash)
(Fig 2a). We verified this response map (specifically the receptive field border location) by
having monkeys make saccades to targets appearing in locations which were inside and outside
LIP represents the visual location of saccade targets of the cell’s receptive field. We then made an array of 30 points along a straight line from the center of the receptive field to the fixation point, spanning the receptive field border (Fig. 2a), and recorded the response of the neuron to saccades to each of the points (chosen pseudorandomly) to evaluate the baseline receptive field and the saccadic amplitude and gain associated with each saccade target in the array (Figures 2c and 2d). We then studied the effect of saccadic adaptation on the on response of the neurons. We took advantage of the fact that saccadic adaptation induced for a single saccade vector partially generalizes to saccades of different amplitudes along the same direction (Semmlow et al., 1989; Frens and Van Opstal, 1997; Straube et al., 1997; Noto et al., 1999). During the adaptation phase, we began by stepping each target backwards a fixed percentage (usually 90%) of the running average saccade gain (defined as the ratio of saccade amplitude to initial target eccentricity). As the adaptation process continued, we increased the size of the backward step, shifting the target to a location at 90% of the mean gain of the last 21 saccades to all targets (Fig 2b, black line), such that each target was stepped back the same percentage of gain (Fig 2b, gray line), but the backstep for any particular target was proportional to that target’s eccentricity and thus a different actual size. The monkey received a reward only after it fixated the new target location, regardless of whether or not it made a corrective saccade. Because the monkeys were allowed to make a corrective saccade, the degree of adaptation did not exert any reward contingency. Because of the huge number of trials necessary to complete a given experiment, we were only able to record from a single neuron during an experimental day. We excluded neurons from the analysis that we were not able to hold through an adaptation process of at least one rate constant.

In this set of experiments, we used backwards (gain reduction) adaptation as some evidence suggests that it is capable of higher gain changes than forward (gain increasing) adaptation (Straube et al., 1997), and because most LIP receptive fields have a clearer medial border than lateral border (Ben Hamed et al., 2001).

**Analysis Methods**

We analyzed the data using MATLAB (MathWorks, Natick, MA). We calculated spike density functions by convolving the spike train with a Gaussian of $\tau=10$ ms. The time of saccade initiation was automatically registered by the computer’s saccade detector when either vertical or horizontal eye velocity exceeded 150 deg/sec for a sufficient duration, and was verified by the
LIP represents the visual location of saccade targets. Neural data was sorted and digitized using the MEX system (available by download from lsr-web.net).

**Saccadic Adaptation Magnitude**

We fit the saccade gain of each trial over the course of adaptation to an exponential function. We defined post-adaptation trials as trials occurring after one rate constant of decay. To calculate an adaptation magnitude value for each session, we subtracted the mean amplitude of all post-adaptation saccades from the mean amplitude of all pre-adaptation saccades. Our data analysis aimed to determine whether the firing rate of neurons in LIP better represented the amplitude of the saccade executed or the initial target location. Saccadic adaptation changes the saccade amplitudes associated with a constant set of initial target locations. If LIP represented saccade amplitude, the same firing rate should be associated with the same saccades regardless of adaptation, but it should be associated with different target locations before and after adaptation; if LIP represented target location, the same firing rate should be associated with the same target location regardless of adaptation, but with different saccade amplitudes before and after adaptation.

To compare these two potential outcomes, we analyzed the responses of LIP neurons in two ways; by saccade amplitude and by target location. The basic logic of our analysis is that for every cell, a particular firing rate will be associated with two values; a saccade amplitude and a target location. For each cell we examined the target location and saccade amplitude associated with a given firing rate before and after adaptation. For cells studied with the memory-guided saccade task we calculated firing rate for three epochs: the first 200 ms after the target appearance (visual epoch), 200 ms after target appearance to 100 ms before the saccade began (delay period epoch), and 100 before the saccade to the beginning of the saccade (presaccadic epoch). For cells studied with the visually guided saccade task we used two epochs: the first 100 ms after the appearance of the target (visual epoch) and 100 ms before the beginning of the saccade (presaccadic epoch). We then took 5 spike/s bins and calculated the mean target location and saccade amplitude associated with the trials in each bin for the pre- and post-adaptation periods. We included in this analysis every trial whose firing rate lay in a bin whose values were found in both the pre- and post-adaptation phases. We then calculated the difference in saccade amplitude and target location for each bin for the pre- and post-adaptation periods. To get a single value for every cell for each adaptation session we averaged these differences. If
LIP represents the visual location of saccade targets. LIP represented target location the mean difference in target location value should not change as a function of saccadic adaptation, but the mean value of saccade amplitude should change as a function of the amount of adaptation. Conversely, if LIP represented saccade amplitude, the mean difference of saccade amplitude should not change but the mean value of target location should vary as a function of the amount of adaptation.

**Results**

**Saccadic adaptation.**

Both monkeys exhibited saccadic adaptation which could be fit with exponential functions (Fig 2b, dashed line $R^2 = 0.32$) with variable time constants and magnitudes similar to those previously reported (Straube et al., 1997; Noto et al., 1999). The amount of adaptation and the number of trials required to adapt on any single day varied greatly; the mean reduction in saccade amplitude was $3.83^\circ$ (SD = 2.17), with a mean rate constant for monkey B = 151 trials (SD = 391) and a mean rate constant for monkey C = 430 trials (SD = 207). In the pre-adaptation block of trials, monkeys made slightly hypometric saccades to each target location (Fig 2c and d, open symbols). By the post-adaptation phase, monkeys reduced their saccade amplitudes and their saccade gains at each target location (Fig 2c and d, closed symbols). The saccadic adaptation magnitude achieved for the example session shown was $6.48^\circ$.

**Effect of saccadic adaptation on neural activity.**

We recorded activity from 30 cells from two monkeys (12 cells in monkey B and 18 cells in monkey C) for the over a thousand trials that were required for the saccadic adaptation experiment in the memory-guided delayed saccade adaptation condition, and 24 cells (17 in monkey B and 7 in monkey C) in the visually-guided saccade adaptation condition. Every cell had visual, delay-period, and presaccadic activity in the memory-guided saccade task. Both monkeys showed qualitatively similar results, so for the subsequent analyses their data is combined. The receptive field profiles of these cells varied. We attempted to fit each cell to a Gaussian, log Gaussian, Weibull and linear functions and then compared the $R^2$ value for each fit to determine which described the response profile best. The response profile of 10 neurons to the linear array of test stimuli could be best fit with a simple Gaussian, 8 neurons with a log Gaussian, 3 neurons with a Weibull function, and 9 neurons with a straight line (Fig 3).

For each cell, we asked if its activity represented the target location or the saccade necessary to acquire it. Because we used memory-guided saccades in this task, we were able to
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examine the relationship between the neural response and the magnitude of saccadic adaptation in three distinct temporal epochs; visual, (first 200 ms after target onset) (Fig 4a), delay (200 ms after target onset to 100 ms before the beginning of the saccade) (Fig 4b), and presaccadic (100 ms before the beginning of the saccade) (Fig 4c). In the example shown, we plotted neural activity on each trial before saccadic adaptation (black symbols) and after saccadic adaptation (red symbols) as a function of target location (Fig 4 second row: d,e,f) and saccade amplitude (Fig 4 third row: g,h,i). If the activity in LIP represented the target location before and after adaptation, we would expect that there would be no difference in the mean target location associated with a given firing rate, but the amplitude of the saccade associated with a given firing rate should change with adaptation. Conversely, if LIP activity represented saccade amplitude we would expect there would be no difference in the saccadic amplitude associated with a given firing rate but the associated target location should change.

For the example cell (Fig 4), the firing rate associated with a given visual target did not change with adaptation, but the firing rate associated with a given saccade amplitude changed with an amount close to the amount of adaptation itself. To quantify this, we calculated the pre- and post-adaptation differences for every firing rate occurring in both pre and post-adaptation phases, using 5 spike/s bins, and then calculated the mean differences for each session. For the example cell, each difference value is plotted against its associated firing rate bin; differences in saccade amplitude for pre vs. post-adaptation are in open symbols, differences in target location in filled symbols (Fig 4, j,k,l for visual, delay and presaccadic epochs, respectively). We averaged these differences across all firing rate bins to arrive at two values per epoch for each session; the mean difference in target location and the mean difference in saccade amplitude. For this example cell, using the visual epoch, the mean difference in target values associated with a given firing rate before and after adaptation was -0.01 °, and the mean difference in saccade amplitude was 5.94 °. For the delay epoch the difference in target values was -0.17 ° and the mean difference in saccade amplitude was 5.83 °, and in the presaccadic epoch the mean difference in target values was 0.27 °, and the mean difference in saccade amplitude was 6.09 °.

In each epoch, the difference in saccade amplitude was similar to the amount of adaptation in this session (6.48°) and the difference in target location was close to zero. This relationship was true for the population of the LIP neurons; in the memory-guided saccade task the mean difference in saccade amplitude for all cells was not different from the degree of adaptation
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achieved for that session (Wilcoxon rank sum test, visual epoch \( p = 0.51 \), delay epoch \( p = 0.40 \),
presaccadic epoch \( p = 0.99 \)), while the mean difference in target location was (Wilcoxon rank
sum test, \( p < 0.001 \) for visual, delay and presaccadic epochs).

By including every trial whose firing rate lay in a bin whose values were found in both
the pre- and post-adaptation epochs, we excluded a few outliers, but included over 98.0% of the
trials for each epoch, both pre and post-adaptation (Memory-guided saccade task: Visual epoch,
mean percent of trials included from each cell pre-adaptation = 98.0\%, s.d. = 2.0\%, post-
adaptation = 98.0\%, s.d. 2.0\%, Delay epoch, mean percent of trials included from each cell pre-
adaptation = 99.0\%, s.d. 1.0\%, post-adaptation = 98.0\%, s.d. =2.0\%, Presaccadic epoch, mean
percent of trials included from each cell pre-adaptation = 99.0\%, s.d. = 0.4\%, post-adaptation =
99.0\%, s.d. = 1.0\%. Visually-guided saccade task: Visual epoch, mean percent of trials included
from each cell pre-adaptation = 99.0\%, s.d. = 1.0\%, post-adaptation = 99.0\%, s.d. = 1.0\%,
Presaccadic epoch, mean percent of trials included from each cell pre-adaptation = 99.0\%, s.d.
1.0\%, post-adaptation = 99.0\%, s.d. = 2.0\%).

We found the same result, that LIP activity represents the target location and not the
saccade amplitude, across the population. For each epoch we regressed the difference in visual
target values and difference in saccade amplitude values for each cell against the actual amount
of adaptation (Fig 5). For the visual epoch the difference in saccade amplitude values correlated
well with the actual adaptation magnitude (Fig 5a, open symbols, \( R^2 = 0.83 \), \( p<0.001 \), slope=
1.01) but there was no correlation of the difference in visual target values with adaptation (Fig
5a, filled symbols, \( R^2 = 0.02 \), \( p=0.45 \), slope=0.06). For the delay epoch the difference in saccade
amplitude values correlated well with adaptation magnitude (Fig 5b open symbols, \( R^2 =0.82 \) \( p
<0.001 \), slope = 0.94) and the difference in visual target values did not (Fig 5b, filled symbols \( R^2
=0.02 \) \( p=0.44 \), slope = 0.07). The same was true even for the presaccadic epoch; the difference
in saccade amplitude values correlated well with adaptation magnitude (Fig 5c, open symbols, \( R^2 =0.82 \) \( p<0.001 \), slope = 0.86) and the difference in visual target values did not (Fig 5c, filled
symbols, \( R^2 =0.007 \) \( p =0.64 \), slope = -0.05). Thus, activity in LIP reliably represents the target
location but not the amplitude of the saccade throughout all three epochs of the memory-guided
delayed saccade task.

In order to insure that our results were not limited to a single type of task, we studied an
additional 24 cells in a simple visually-guided saccadic adaptation task. We found similar results
LIP represents the visual location of saccade targets using visually-guided saccades, for both the visual (Fig 6a saccade amplitude values, open symbols, $R^2 = 0.76$ p <0.01, slope =1.01, visual target values, filled symbols, $R^2 =0.004$ p =0.76, slope =-0.10) and presaccadic epochs (Fig 6b saccade amplitude values, open symbols, $R^2 = 0.66$ p <0.001, slope = 0.88, visual target values, filled symbols, $R^2 = 0.05$ p = 0.27, slope =-0.12).

The mean difference in saccade amplitude for all cells was not different from the degree of adaptation achieved for that session (Wilcoxon rank sum test, visual epoch p =0.9, presaccadic epoch p = 0.75) while the mean difference in target location was (Wilcoxon rank sum test, p <0.001 for visual and presaccadic epochs).

**Discussion**

In these experiments we used the technique of saccadic adaptation to ask if activity in LIP represented the saccade that the monkey actually made or the location of the target to which the monkey made the saccade. We found that activity in LIP reliably signals the visual location of the stimulus and not the amplitude of the saccade the monkey used to acquire the stimulus. This in turn suggests that although LIP, and perhaps the parietal lobe in general, may very well transfer visual information to the motor system, it serves as a conduit and does not effect the transformation of that visual information into actual movement parameters.

*Previous studies of whether LIP represents target or saccade.*

Several lines of inquiry have suggested that LIP effects a sensorimotor transformation. Platt and Glimcher asked the same question we ask here, and concluded that activity in LIP reflected the movement, not the target (Platt and Glimcher, 1998). They relied on a different method, which may explain our contradictory results. In their study, the authors used a Gaussian model to fit the responses of all LIP neurons during delayed saccades to multiple targets, grouped by either target location or saccade endpoint relying on natural variability in endpoint scatter to distinguish the two parameters. They found that the Gaussian model accounted for slightly more response variance based on saccade amplitude. However, the separation between the saccade endpoint and target location that we are able to achieve using saccadic adaptation is far greater than the variability in saccade endpoints that occurs naturally, strengthening our results. In addition, we found that although some cells’ response profiles could be fit by a Gaussian, others could be best fit by a log Gaussian, a Weibull function, or just a straight line, so assuming that all neurons adequately fit a Gaussian model may not have been appropriate.
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Another method of separating the intended and actual saccade endpoint in space is by using an antisaccade task in which a visual stimulus directs a saccade in the opposite direction. Gottlieb and Goldberg recorded from LIP while a monkey was instructed to make a saccade either to the visual stimulus (prosaccade) or directly opposite of the visual stimulus (antisaccade). They reported that the majority of LIP cells encoded the location of target in both tasks, but a minority of cells did shift their activity so that they described the saccade goal in the presaccadic period (Gottlieb and Goldberg, 1999). In a subsequent antisaccade study, Zhang and Barash described cells with visual, but not presaccadic, responses in the memory-guided delayed antisaccade task responded before antisaccades to their receptive field. This response had a somewhat longer latency than their visual responses, and was interpreted as a sensorimotor transformation (Zhang and Barash, 2004). However, in both of these studies the locus of attention and the endpoint of the eye movement are not dissociated. During the delay, the activity of the LIP cell may change to reflect a shifting locus of attention preceding the eye movement, but not the motor command itself.

Previous experiments suggest that the perceptual system may be using a signal similar to the one we see in LIP which may not match the signal sent to the eye muscles. For example, it has been shown that attention, as measured by perceptual threshold, lies at the target of saccade, even when the eye lands elsewhere due to endpoint variability (Deubel and Schneider, 1996) or saccadic adaptation (Ditterich et al., 2000). In addition, under conditions of saccadic adaptation, psychophysical evidence suggests that the perceptual system is not aware of downstream changes in motor commands. Bahcall and Kowler demonstrated this by having subjects adapt their saccades and then judge the location of a brief probe stimulus presented 250 ms after the saccade. Subjects mislocalized the probe, reporting locations relative to the saccade endpoint as though the eye had reached the intended target, even though it had actually landed away from it (Bahcall and Kowler, 1999). These results suggest that perceptual system assumed that the original target had not moved and the saccade was accurate, and therefore could serve as a reference point to localize the stimulus. Awater et. al. similarly found that subjects mislocalized stimuli presented at time points well before the saccade as though the perceptual system was uninformed about the adaptation state. In addition, they found that this mislocalization only occurs for targets flashed between the initial and final target positions (Awater, 2004). Our findings in LIP are consistent with these psychophysical results.
However, in some circumstances, information about the actual eye movement may be available to guide behavior. Collins et al. reported that the perceptual system is affected by changes in motor space caused by adaptation (Collins et al., 2007). Tanaka et al. found that if the first saccade in a double-step task is adapted, subjects are able to compensate in the second saccade, resulting in accurate performance (Tanaka, 2003). Awater et al. also found that saccadic mislocalization occurring around the time of the saccade compressed space at the actual, and not intended, saccade endpoint (Awater, 2004). Under the conditions of these tasks, it is possible that information regarding eye position information, such as an eye proprioception signal (Zhang et al., 2008) or cerebellar information regarding adaptation state is being used by the subject to adjust behavior. Although these signals may be available to guide behavior, our results suggest that they are not reflected in LIP.

Other studies using saccadic adaptation.

Our results indicate that LIP is uninformed of the oculomotor system’s adaptation state. This may be because the adaptation signals are likely to originate downstream, closer to the actual muscles affecting the eye movement. The locus of saccadic adaptation has been investigated using single unit recording, stimulation and lesion approaches. It has been demonstrated that saccadic adaptation occurs at a point where the saccade is represented as a vector (Hopp and Fuchs, 2006) and affects gaze before it is separated into its eye and head components (Phillips et al., 1997; Cecala and Freedman, 2009). Neurons in the superior colliculus, even neurons which do not have visual responses, represent target location and not saccade amplitude in both the head-fixed (Frens and Van Opstal, 1997; Quessy et al., 2010) and unrestrained conditions (Fernandez-Ruiz et al., 2007; DeSouza et al., 2011). Electrical stimulation of the superior colliculus evokes the adapted saccade when the stimulation current is low, although at high current levels it evokes an unadapted saccade, perhaps because the stronger stimulation signal overwhelms the adaptation signal (Edelman and Goldberg, 2002).

The actual adaptation of saccade amplitude is more likely to occur in the cerebellum. Recordings made of complex spikes in the oculomotor vermis (Soetedjo and Fuchs, 2006) and stimulation of the midbrain tegmentum (Kojima et al., 2007) provide evidence that the learning signal is present at the level of the cerebellum. Patients with cerebellar degeneration or lesions show impairments in saccadic adaptation (Straube et al., 2001), and monkeys with lesions of the cerebellum, particularly the oculomotor fastigial nucleus (OFN) and the cerebellar vermis,
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cannot rapidly adapt their saccades (Optican and Robinson, 1980; Barash et al., 1999).

Robinson et al. demonstrated that the caudal fastigial nucleus (CFN) of the cerebellum is
necessary for the expression, but not the induction of saccadic adaptation. They showed this by
temporarily inactivating the CFN and having the monkey perform a saccadic adaptation task (in
which the monkey did not demonstrate any adaptation). They then placed the monkey in a dark
room while the CFN inactivation wore off. When they tested the monkey afterwards, adaptation
was observed (Robinson et al., 2002).

Our physiological results demonstrate that LIP represents retinal target location, a signal
which must be transformed to the amplitude of the desired saccade elsewhere. One possibility is
that this signal is sent to the cerebellum that in turn effects a sensorimotor transformation by
specifying the parameters of the movement itself, and, if necessary, modifies the brainstem
activity that drives the saccade. However, although LIP conveys information about the
impending saccade target, it does not convey the actual eye movement command.

Disclosures

No conflict of interest.

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the data. SCS, MHP and MEG performed the surgery and prepared the manuscript. MEG
conceived of the idea of using saccadic adaptation to study sensorimotor transformation in LIP
and collaborated in all aspects of the project.

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LIP represents the visual location of saccade targets

**Figure Legends**

Figure 1. Adaptation task. A. Monkeys fixate the central point to initiate a trial. A saccade target appears for 100 ms after which there is a random delay of 600-900 ms. The extinction of the fixation point serves as a cue for the monkey to make an eye movement to the remembered location of the target. Once the monkey initiates the saccade, the target reappears at a shifted location. B. Monkeys shorten their saccade amplitudes after adaptation. Target duration and location indicated by the solid trace, eye movement duration and position indicated by the dashed trace. The first panel shows the monkey accurately making memory-guided saccades to the target before adaptation starts. The second panel shows an early adaptation trial in which the monkey initially overshoots the shifted target location and must make a corrective saccade to acquire it. The third panel shows a trial from the post-adaptation phase in which the monkey makes an eye movement directly to the shifted location, eliminating the corrective saccade.

Figure 2. Target locations and adaptation. A. Receptive field map with overlaid target locations. We mapped the visual field using spots 5° apart on a 40° by 40° degree grid, flashed while the monkey fixated the center of the screen (marked by the x on the map). Each square of the map corresponds to a spot location. The color of the grid corresponds to the neural response – the brighter the color the more the response. The scale bar on the right shows the firing rates associated with each color. The receptive field was in the lower right corner of the screen. For saccadic adaptation we used thirty potential target locations (white circles), selected based on this map such that they would fall along a line which spanned at least one boundary of the cell's receptive field. B. Time course of saccadic adaptation. Ordinate: saccadic gain. Abscissa: trial number. Black line: target step ratio (the ratio of final to initial target location. The pre-adaptation value is 1) Grey line: a running average of the previous 21 points with the thickness of the line being the standard error of the mean. Dotted line: best fit exponential decay. First vertical line: beginning of adaptation. Second vertical line: beginning of post-adaptation period, defined as the trials after the gain had decreased by 1 rate constant. C. Saccade amplitudes as a function of target location across the target array. Ordinate: mean saccadic amplitude for given target location. Abscissa: target location. Open circles: pre-adaptation values. Filled circles: post-adaptation values. D. Saccade gains as a function of target location (same conventions as 2 C).

Figure 3. Examples of receptive field profiles. Ordinate axis is firing rate in spikes per second, abscissa is target location in degrees. Each point represents the firing rate (using the
LIP represents the visual location of saccade targets. The visual epoch, the 200 ms following stimulus onset, is associated with a target location, the solid line is the curve resulting from fitting the points to one of four models. The $R^2$ value reflects the goodness of fit for each cell. Example cells best fit by a A. Gaussian, B. Log Gaussian, C. Weibull and D. Linear functions.

Figure 4. Example cell responses compared pre and post-adaptation. First row: Spike density and raster diagrams in the unadapted memory-guided delayed saccade task, with the target location at the most effective location for the cell. The ordinate is mean firing rate (white line, with the SEM shown by the black line) and the abscissa is time in ms, with target onset at 0. For the rasters each row is a single trial and each point is a single action potential. The vertical line represents the event on which the rasters and spike density diagrams were synchronized. The shaded zones are the epoch from which the data in the adjacent scatter plots were taken. A. Visual epoch: Raster synchronized on the visual target appearance, visual epoch shaded in gray, saccade initiation times for each trial indicated by an x in the raster plot. B. Raster aligned on visual target appearance on left, saccade initiation on right. Shaded area indicates the delay epoch (variable duration depending on saccadic reaction time). C. Raster aligned on saccade initiation, pre-saccadic epoch indicated by shaded area, target appearance times for each trial indicated by an x in the raster plot. Second row: Firing rate in pre-adaptation trials (black symbols) and post-adaptation trials (red symbols) grouped by target location for the visual epoch (D), delay epoch (E) and presaccadic epoch (F). Third row: Firing rate in pre-adaptation trials (black symbols) and post-adaptation trials (red symbols) grouped by saccade amplitude for the visual epoch (G), delay epoch (H) and the presaccadic epoch (I). Fourth row: Difference values based on firing rate (ordinate) shown for each 5 sp/s bin size (abscissa). Difference in mean target location associated with each firing rate in filled symbols, difference in mean saccade amplitude associated with each firing rate in open symbols for the visual epoch (J), delay epoch (K) and presaccadic epoch (L).

Figure 5. Population of differences based on target location values and saccade amplitude values compared to the magnitude of saccadic adaptation using memory-guided saccades. A. Each point represents the mean difference in target location for identical firing rates between pre- and post-adaptation values for a given cell during the visual epoch 200 ms following the
LIP represents the visual location of saccade targets. Presentation of the target stimulus. Black solid line is the regression line of the difference values against the magnitude of adaptation (difference in saccade amplitude against adaptation magnitude, open symbols, $R^2 = 0.83$, p < 0.001, slope = 1.01, difference in target location against adaptation magnitude, filled symbols, $R^2 = 0.02$, , p = 0.45, slope = 0.06, dashed lines represent 95% confidence intervals, red solid line is x = y, difference values from a single session are connected by a vertical line.) B. Same conventions as 5a, but for responses in the delay epoch extending from 200 ms after the target appeared to 100 ms before the beginning of the saccade (difference in saccade amplitude against adaptation magnitude, open symbols, $R^2 = 0.82$, p < 0.001, slope = 0.94, difference in target location against adaptation magnitude, filled symbols, $R^2 = 0.02$, p = 0.44, slope = 0.07 ). C. Same conventions as 5a, but for responses during the presaccadic epoch from 100 ms before saccade initiation to the beginning of the saccade (difference in saccade amplitude against adaptation magnitude, open symbols, $R^2 = 0.82$, p < 0.001, slope = 0.86, difference in target location against adaptation magnitude, filled symbols, $R^2 = 0.007$, p = 0.64, slope = -0.05).

Figure 6. Population of difference values based on target location values and saccade amplitude values compared to the magnitude of saccadic adaptation using visually guided saccades. A. Same conventions as figure 5. Visual epoch 100 ms following presentation of the target stimulus (difference in saccade amplitude against adaptation magnitude, open symbols, $R^2 = 0.76$, p < 0.01, slope = 1.01, difference in target location against adaptation magnitude, filled symbols, $R^2 = 0.004$, p = 0.76, slope = -0.10). B. Same conventions as figure 5, presaccadic epoch 100 ms preceding saccade onset (difference in saccade amplitude against adaptation magnitude, open symbols, $R^2 = 0.66$, p < 0.001, slope = 0.88, difference in target location against adaptation magnitude, filled symbols, $R^2 = 0.05$, p = 0.27, slope = -0.12).
LIP represents the visual location of saccade targets

References


LIP represents the visual location of saccade targets.

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LIP represents the visual location of saccade targets


Figure 1, Steenrod

a. Fixation (450 ms)
   Saccade target appears (100 ms)
   Delay (600-900 ms)
   Fixation off (go signal for monkey to make saccade)
   Target reappears at shifted location

b. pre-adaptation  early adaptation  post-adaptation

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Figure 2, Steenrod

a.  

b. Pre Early Post adaptation

Saccade gain, single trial
Mean saccade gain
Exponential fit (R^2 = .32)
Target shift ratio

Mean saccade amplitude (deg)
Pre adaptation
Post adaptation
x=y

Mean saccade gain

Firing rate (sp/sec)

Target location (deg)

Target location (deg)

Vertical position (deg)

Horizontal position (deg)

Mean saccade amplitude (deg)

Target location (deg)

Target location (deg)

Vertical position (deg)

Horizontal position (deg)

Firing rate (sp/sec)
Figure 3, Steenrod

Target location

Firing rate (sp/sec)

a. Gaussian

\[ R^2 = 0.76 \]

b. Log Gaussian

\[ R^2 = 0.56 \]

c. Weibull

\[ R^2 = 0.52 \]

d. Linear

\[ R^2 = 0.78 \]
Figure 4, Steenrod

**a. Visual epoch**
- Firing rate (spikes/second) vs. Time (ms)

**b. Delay epoch**
- Firing rate (spikes/second) vs. Time (ms)

**c. Presaccadic epoch**
- Firing rate (spikes/second) vs. Time (ms)

**d. Pre adaptation trial**
- Firing rate (spikes/second) vs. Target location (degrees)

**e. Post adaptation trial**
- Firing rate (spikes/second) vs. Target location (degrees)

**f.**
- Firing rate (spikes/second) vs. Target location (degrees)

**g.**
- Firing rate (spikes/second) vs. Saccade amplitude (degrees)

**h.**
- Firing rate (spikes/second) vs. Saccade amplitude (degrees)

**i.**
- Firing rate (spikes/second) vs. Saccade amplitude (degrees)

**j.**
- Difference value (degrees) vs. Firing rate (5ms bins)

**k.**
- Difference value (degrees) vs. Firing rate (5ms bins)

**l.**
- Difference value (degrees) vs. Firing rate (5ms bins)
Figure 5, Steenrod

(a. Visual epoch)  
(b. Delay epoch)  
(c. Presaccadic epoch)

Mean difference value (degrees) vs. Adaptation magnitude (degrees)
Figure 6, Steenrod

a. Visual epoch

b. Presaccadic epoch

Adaptation magnitude (degrees)

Mean difference value (degrees)