Focused Attention Modulates Visual Responses in the Primate Prefrontal Cortex

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DeSouza, Joseph F. X. and Stefan Everling. Focused attention modulates visual responses in the primate prefrontal cortex. J Neurophysiol 91: 855–862, 2004. First published September 3, 2003; 10.1152/jn.00273.2003. Several current models propose an important role of the prefrontal cortex (PFC) in attention. To test the effects of attention in PFC, we recorded from PFC neurons in monkeys performing a task in which they had to attend to one hemifield and wait for a single stimulus that matched a previously presented cue. Neurons exhibited a slight decrease in their initial response and an enhanced activity late in the response to a stimulus at the cued location. The data demonstrate attentional effects on the activity of PFC neurons but they also show that single visual stimuli are initially represented in the activity of PFC neurons even when they are behaviorally irrelevant.

INTRODUCTION

Natural visual scenes contain many different objects and features that cannot be fully processed at any given moment. Therefore attentional mechanisms are needed to select those objects that are currently relevant to behavior (Broadbent 1965; Desimone and Duncan 1995). Neural correlates for spatial attention have been observed in the “dorsal visual pathway” (Bushnell et al. 1981; Colby et al. 1996; Constantinidis and Steinmetz 2001; Nakamura and Colby 2000; Treue and Maunsell 1999), which has been implicated in spatial visual processing (“where”). Conversely, neural correlates for object attention have been found in the “ventral visual pathway” (Chelazzi et al. 1993, 1998), which has been implicated in feature and object-related visual processing (“what”).

In the real world, however, a separation between spatial- and feature-related attention rarely occurs. When we attend to a certain location, we usually look for a particular person or object. Indeed, behavioral studies have shown that attending to a particular location in the visual field enhances feature discrimination at that location (Henderson 1996; Henderson and Macquistan 1993; Prinzmetal et al. 1986). This indicates that neural processes mediating spatial attention have access to those mediating feature and object analysis. Most studies, however, have found only very local effects of spatial attention in ventral visual areas (Luck et al. 1997; Moran and Desimone 1985; Reynolds et al. 1999). Strong attentional modulation of neural activity occurs typically only if stimuli are close together, within the same neuron’s receptive field.

One region that may play a role in the integration of spatial attention and stimulus analysis is the prefrontal cortex (PFC), which receives inputs from both dorsal and ventral visual streams (Pandya and Kuypers 1969; Petrides and Pandya 2002; Ungerleider et al. 1989) and integrates this information for the guidance of voluntary goal-directed behavior (Fuster 1991; Miller and Cohen 2001; Passingham 1993).

Recent single neuron studies of working memory in monkeys have shown that many PFC neurons convey both object and location information during delay periods (Rainer et al. 1998a; Rao et al. 1997; White and Wise 1999). Human neuroimaging studies also indicate that spatial and object working memory largely overlaps in the PFC (Nystrom et al. 2000; Owen et al. 1999; Postle et al. 2000). Attentional modulation has been found during delay periods in PFC neurons (Rainer et al. 1998b). Further, target/nontarget discriminations of PFC neurons are modulated by focused spatial attention (Everling et al. 2002). Many of these PFC neurons discriminated between target and nontarget stimuli at an attended location by showing enhanced visual responses to target stimuli. This enhancement was effectively eliminated when the monkey attended to a nontarget stimulus that was presented simultaneously in the opposite hemifield.

To investigate whether spatial- and stimulus-related attention modulate the responses of PFC neurons to single stimuli, we employed a variation of the delayed-match-to-sample task (see Fig. 1). On each trial, while the monkey fixated a central fixation point, a spatial location was cued by briefly presenting one of two stimuli in the left or right visual field. After a delay, one to two test stimuli were presented sequentially. The task was to attend to the cued side and wait for a test stimulus on this side that matched the cue stimulus and then to fixate it. During this delayed-match-to-stimulus-and-location (DMSL) task, we recorded the activity of neurons in the lateral PFC (Fig. 2, A and B). This task allowed us to investigate the effects of spatial and stimulus attention on neural responses to identical visual stimuli (Fig. 1, panel 4 in each row). We found evidence for effects of spatial but not of stimulus-related attention in prefrontal neurons.

METHODS

The subjects in this study were two male rhesus monkeys (Macaca mulatta, 5 and 6 kg). All training, surgical, and experimental procedures were in accordance with the Canadian Council on Animal Care policy on the use of laboratory animals and approved by the Animal Use Subcommittee of the University of Western Ontario Council on Animal Care. Animals were under the close supervision of the university veterinarians.

Both animals were prepared for chronic experiments by undergoing

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surgical procedures to place an implant on their skull. The implant contained both a recording chamber and a head bolt. Monkeys were sedated for the surgery with ketamine hydrochloride (10–15 mg/kg im). Atropine (0.05 mg/kg atropine sc) was given to reduce bradycardia and salivary secretions. Anesthesia was initiated with a bolus of propofol (2.0 mg/kg) and maintained with propofol (0.2 mg/kg/min) and midazolam (0.35 mg/kg/min) administered through an intravenous cannula throughout the surgery. Heart rate, blood pressure, respiratory rate, and body temperature were monitored closely for the duration of the surgery. For a 10-day period after surgery, animals received a daily dose of antibiotic (amoxicillin orally) to prevent infection. Animals were also given the analgesic buprenorphine hydrochloride (0.01 mg/kg im) postoperatively to alleviate any potential discomfort.

In a first surgery, a head implant was constructed from dental acrylic and anchored to the skull with titanium screws. A titanium head bolt to restrain the head was anchored into the acrylic implant. After training on the behavioral paradigms, animals underwent a second surgery for preparation of eye movement recordings using the magnetic search coil technique (Fuchs and Robinson 1966) and for

![FIG. 1. Delayed-match-to-stimulus-and-location task. Example stimulus sequences (4 of a possible 16 conditions). Each trial began when the monkey fixated (curved arrow) a small dot in the center of the screen. A cue (stimulus A or stimulus B) appeared to the left or right. After a delay, 1 to 2 test stimuli were presented sequentially. The monkey had to maintain central fixation (dotted circle) until a test stimulus matched both the stimulus and the location of the cue stimulus and then fixate it (straight arrow).](image)

![FIG. 2. Recording locations. A: magnetic resonance imaging. High-resolution inversion prepared 3D T1-weighted coronal anatomical slice of the brain of monkey P (1 mm slice thickness). Vitamin E markers inside the grid were used to reveal its orientation and location (schematic grid drawn on for visualization). B: location of recording sites, with numbers of cells showing significant excitatory visual responses (n = 44, see text).](image)
preparation of chronic neuron recordings. A preformed eye coil (3 turns of stainless steel wire, Cooner Wire, Chatsworth, CA) was implanted into one eye behind the conjunctiva (Judge et al. 1980). The coil lead was passed subcutaneously to the acrylic implant that anchored the connector. A craniotomy (19 mm diam) was performed over the left principal sulcus (A-P: 31 mm, M-L: 18 mm). A recording cylinder suitable for MRI (Crist Instruments, Hagerstown, MD) was placed over the trephination and dental acrylic was applied so that the entire implant was attached firmly to the skull.

**Behavioral paradigms**

DELAyED-MAtCh-TO-STIMULUS-AND-LOCAtION TASK. Monkeys performed a DMSL task (Fig. 1) (Rainer et al. 1998a). Two pictures were used as stimuli throughout the experiment. They were “real world” pictures on white background (2° × 2°), easily distinguishable from each other and from the black monitor screen. They were multicolored and contained complex shapes. Each trial started with the presentation of a central fixation point (FP, white dot, 0.2°). After 300 ms, a cue stimulus was presented for 300 ms either to the left or right of the FP. The monkeys were required to remember both the location and the identity of the cue. After a 1-s delay period, a test stimulus was presented. On 25% of the trials, it was a match (the cue stimulus appearing in the same location), on 25% it was a stimulus nonmatch (a different stimulus but appearing in the same location), on 25% it was a location nonmatch (the same stimulus but appearing in the opposite location), and on 25% it was a stimulus and location nonmatch (the other stimulus appearing in the opposite location). On nonmatch trials, there was another delay (500 ms) always followed by the match stimulus. The monkeys were required to look at the FP and maintain central fixation (window, 0.5° × 0.5°) until the match stimulus appeared, and then immediately to fixate it (response window 600 ms from match onset, size 4° × 4°). On successful trials, a juice reward was given immediately after the saccade to the match stimulus. Monkeys were well trained on the task. They, on average, completed 86% of the trials correctly, missed a match on 13% of the trials, and looked toward a nonmatch stimulus on 1% of the trials. Monkeys received juice until satiation, after which they were returned to their home cage. Records were kept of the weight and health status of the monkeys, and additional water and fruit was provided.

**BEEHAVORIAL CONTROL AND PRESENTATION OF VISUAL STIMULi**

Two Pentium PCs running CORTEX, a program developed in the laboratory of Dr. Robert Desimone (National Institute for Mental Health) for conducting neurophysiological and behavioral experiments, were used to present the stimuli, to control the behavioral paradigms, and to deliver the rewards. Monkeys were seated comfortably in a primate chair within a sound attenuating isolation chamber with their heads restrained and a juice-spout placed at their mouth for computer-controlled reward delivery (Crist Instruments). The stimuli were presented on a 21-inch color computer screen 42 cm in front of the animals. During the training after the first surgery, horizontal and vertical eye movements were monitored at 60 Hz using a video eye tracker (ISCAN, Boston, MA). During the recording sessions after the second surgery, horizontal and vertical eye movements were sampled at 1000 Hz using a magnetic search coil system (David Northmore Inst., Newark, DE) in monkey K. The eye coil in monkey P broke after a few days and the video eye tracker was used to monitor the eye positions in this monkey.

**Electrophysiology**

Neuronal activity was recorded extracellularly from the lateral prefrontal cortex with commercially available dura-puncturing tungsten microelectrodes (UEWLGDSMMNIE, FHC Inst., Bowdoinham, ME). Arrays of two to eight electrodes were driven within the recording chamber by custom-designed screw minimecrodrives (Nichols et al. 1998). The microdrives were mounted on a Delrin grid (Crist Instruments) with 1-mm spacing between adjacent locations inside the recording chamber. The grid array was visualized in situ by MRI (Fig. 2A) and registered with the anatomy (Fig. 2B). Neural activity was amplified, filtered, and stored for off-line cluster separation applying principal component analysis with the Plexon MAP system (Plexon, Dallas, TX). Horizontal and vertical eye positions were also stored in the Plexon MAP system. Neurons were randomly sampled, and no attempt was made to prescreen neurons for task-related responses. Within a recording session, the average number of trials receiving a correct response was 219 (approximately 14 trials for each of the 16 conditions, with only 4 of 16 conditions shown in Fig. 1).

**Data analysis**

Data analysis was performed using Matlab (Mathworks) and custom-designed software. Saccade onset was defined as the time when the radial velocity exceeded 30°/s and the end of the saccade was defined as the time when the radial velocity fell below 30°/s. Trials associated with errors (broken or incorrect fixation, failure to fixate a match stimulus) were excluded automatically from analyses of neural activity. Each trial was visually expected, and trials with saccades during required fixation intervals (cue presentation, delay, and nonmatch test stimuli) were excluded from further analysis by an experimenter if necessary.

**Neuron classification**

Neurons were classified as having a visual-response and stimulus and location preferences were determined for each neuron based on the activity in a window from 100 to 400 ms after cue stimulus onset after the subtraction of baseline activity (200-ms interval ending at cue stimulus onset). For each cell, we performed a mixed three-way ANOVA with “between” factors, cued location (ipsilateral or contralateral to the recording site) and stimulus (stimulus A or B), and “within” factor, period (baseline period or stimulus period). Neurons were classified as having visual-related activity if they showed a main effect of location, a main effect of stimulus, an interaction of location with stimulus, or a main effect of period (P < 0.01). A neuron’s preferred location was defined as the cueing location that yielded the maximal deviation from baseline activity. Conversely, a neuron’s preferred stimulus was defined as the cueing stimulus that yielded the maximal deviation from baseline activity. Neurons with visual-related activity were classified as having excitatory responses if the maximal deviation from baseline activity was positive and as having inhibitory responses if the maximal deviation was negative. Delay activity was assessed in a similar way on the activity in a window from 200 to 1,000 ms after cue stimulus offset after the subtraction of baseline activity.

**Analysis to test stimuli**

The objective of this study was to examine the effects of spatial- and stimulus-related attention on the visual responses of PFC neurons. We therefore analyzed the responses of neurons with visual-related activity to the presentation of the first test stimulus. Data from the second test stimulus were not included in these analyses because the stimulus was always predictable.

All the data were expressed as mean ± SE. Statistical comparisons of neural activity between two conditions were conducted with paired Student’s t-test or, if a test of normal distribution (Kolmogorov–Smirnov test) failed, with the nonparametric Wilcoxon signed-rank test. Significance was accepted at the P < 0.05 level.

**RESULTS**

We recorded the activity of 212 neurons from the lateral PFC of two monkeys (Fig. 2B) in a DMSL task (Fig. 1). Many
neurons showed visual-related responses in the cue and test intervals and some delay-related activity. This is in line with previous studies that examined the discharge properties of PFC neurons in delayed-match-to-sample tasks (Fuster and Alexander 1971; Miller et al. 1996; Wilson et al. 1993). Figure 3 shows the activity of a PFC neuron with visual-related responses on trials in which the test stimulus was the preferred stimulus at the preferred location. The blue line in Fig. 3 represents neural activity on trials in which the cue was also the neuron’s preferred stimulus at the preferred location (location match/stimulus match condition) and the monkey responded by making an eye movement toward the stimulus. The red line shows the neuron’s activity when the cue stimulus was the nonpreferred stimulus at the preferred location (location match/stimulus nonmatch condition) and the monkey was required to maintain central fixation. The black line shows the neuron’s activity on trials in which the cue stimulus was the preferred stimulus but appeared at the nonpreferred location (location nonmatch/stimulus match condition). The green line shows the neuron’s activity on trials in which the cue stimulus was the nonpreferred stimulus that appeared at the nonpreferred location (location nonmatch/stimulus nonmatch condition). Interestingly, the neuron exhibited variations in its response after test stimulus onset between these conditions. It showed a more sustained activity for the location match/stimulus nonmatch condition (red line) than for the location (green line) and stimulus and location (black line) nonmatch condition. The stimulus was identical in these three nonmatch conditions and the monkey was fixating the central fixation spot in all three nonmatch conditions.

A total of 52 neurons (25%) exhibited significant visual-related responses. For our analysis, we focused on the 44 neurons (21%) that exhibited excitatory visual responses in the cueing period (P < 0.01; see METHODS). The small number of neurons with inhibitory responses (8/212 or 4%) did not allow us to make meaningful comparisons between the match and nonmatch conditions.

We found about equal numbers of neurons that preferred stimulus A and B (24/44, or 55%, for stimulus A and 20/44, or 45%, for stimulus B). Consistent with previous reports (Everling et al. 2002; Funahashi et al. 1989; Rainer et al. 1998a; Sakagami and Niki 1994), we found a mild preference for the contralateral hemifield [28/44 or 64% preferred contralateral stimuli (on the right side) and 16/44 or 36% preferred ipsilateral stimuli]. In a two-way ANOVA with factors location (left or right) and stimulus (A or B), 15 neurons (34%) showed a main effect of location, 2 neurons (5%) showed a main effect of stimulus, and 5 neurons (11%) showed an interaction (P < 0.01; see METHODS).

To compare the discharge properties of the neurons in our study with those of previous PFC studies (Funahashi et al. 1989; Rainer et al. 1998a,b; Rao et al. 1997), we also analyzed the delay activity of these neurons. A total of 51 neurons (24%) showed significant delay-related activity. In a two-way ANOVA with factors location (left or right) and stimulus (A or B), 11 neurons (22%) showed a main effect of location, 3 neurons (6%) showed a main effect of stimulus, and 2 neurons (4%) showed an interaction (P < 0.01; see METHODS). Of the 44 neurons with excitatory visual responses, only 16 (36%) also exhibited delay-related activity. Only about half of these neurons had excitatory delay activity (9/16, or 56%). A main effect of location was found in 4 neurons (25%), none showed a main effect of stimulus, and 1 neuron showed an interaction (P < 0.01; see METHODS). This analysis confirmed the well-known findings that PFC neurons exhibit delay-related activity. It also shows that only a subpopulation of excitatory visually responsive neurons in the PFC exhibits such delay activity (Rainer et al. 1998b).

Figure 4 shows the population activity of our sample of 44 PFC neurons with excitatory visual responses during the DMSL task when the preferred stimulus appeared at the preferred location during the first test period. Saccades in the location and stimulus match condition with reaction times under 150 ms were excluded in this analysis (24% of saccades in monkey K and 7% of saccades in monkey P). The activation waveform for matches (solid blue line) is shown as a dashed line 150 ms after test stimulus onset to indicate that activity after this point likely reflects new visual input after the saccade. Reflecting the results of the two-way ANOVA, the population showed a higher cue-related activity for the preferred location but only small differences between the preferred and nonpreferred stimulus. The population showed almost no delay-period activation after the presentation of the cue, which is related to the finding that only about one-third of the neurons

![FIG. 3. Single neuron example. Responses of a single visually responsive neuron for trials in which the test stimulus was the neuron’s preferred stimulus at the preferred location. The first shaded area represents the time of cue presentation. The second shaded area represents the time of test stimulus presentation. Each dot indicates the time of an action potential, and each row represents 1 trial. Below are the spike density histograms with a binwidth of 50 ms. Saccades started in the match condition 150 ms after test presentation, indicated by the dashed blue line.](image-url)
with excitatory visual responses exhibited delay-related activity. Moreover, only about half of these neurons increased their activity during the delay period whereas the other half decreased their activity, thereby canceling out an overall effect of delay-period activation.

To investigate the hypothesis that the visual responses of PFC neurons are modulated by spatial- and stimulus-related attention, we compared the test-related activity between the task conditions. The test stimulus was the preferred stimulus at the preferred location. The first shaded area represents the time of cue presentation. The second shaded area represents the time of test stimulus presentation. Spike density histograms have a binwidth of 50 ms. Saccades started in the match condition 150 ms after test presentation, indicated by the dashed blue line.

We compared the early visual response of PFC neurons in the interval from 80 to 150 ms after test stimulus onset between the task conditions. This interval comprised stimulus-related activity until the onset of the first saccades (>150 ms). Significant differences were found for the population between the match condition and the location nonmatch/stimulus nonmatch condition (Wilcoxon signed-rank test, P < 0.005). A similar result was observed for the comparison between location match/stimulus nonmatch condition with the location nonmatch/stimulus nonmatch condition (Wilcoxon signed-rank test, P < 0.01; see Fig. 5, A and B). No other comparisons were significant during this early response period. This suggests and effect of spatial- but not stimulus-related attention on the initial visual response of PFC neurons in this task.

The most prominent difference between the conditions was, however, a sustained level of late activation on location match/stimulus nonmatch trials (solid line) compared with location nonmatch trials (dotted line) (see Fig. 5A). In the interval 300–500 ms after stimulus onset, the mean discharge rate was 10.8 ± 1.7 spikes/s (range 0 to 48) on location match/stimulus nonmatch trials, 8.8 ± 1.4 spikes/s (range 0 to 41) on location nonmatch/stimulus match trials, and 8.9 ± 1.5 spikes/s (range 0 to 48) on location nonmatch/stimulus nonmatch trials. We could not analyze the activity for match trials as the animals had already generated almost all their saccades to the peripheral stimulus during this period (0% of saccades in monkey K and 2% of saccades in monkey P had reaction times above 500 ms).

To test whether spatial attention modulated the activity of PFC neurons, we compared the activity between location match trials with location nonmatch trials. We found significant differences between location match/stimulus nonmatch trials and location nonmatch/stimulus match trials (Wilcoxon signed-rank test across cells, P < 0.05; Fig. 5C, top) and between location match/stimulus nonmatch trials and location nonmatch.
Discussion

Our results show that visual responses of PFC neurons to a single stimulus are modulated by spatial attention. This modulation took the form of a mild decrease in early responses for location matches and a prominent late enhancement of visual-related activity when the monkey attended to the location of a stimulus compared with when he attended away from the stimulus. This late enhancement was found in the period 300–500 ms after test stimulus onset.

Previous studies have demonstrated spatial attentional modulation of visual responses in both dorsal (Bushnell et al. 1981; Colby et al. 1996; Constantinidis and Steinmetz 2001; Nakamura and Colby 2000; Treue and Maunsell 1996) and ventral visual areas (Luck et al. 1997; Moran and Desimone 1985; Reynolds and colleagues 1999). Neurons in dorsal visual areas show these modulations for single visual stimuli in the absence of simultaneously presented distractors. An attentional enhancement has been found for neurons in the lateral intraparietal area (Bushnell et al. 1981; Colby et al. 1996; Nakamura and Colby 2000) whereas neurons in the neighboring parietal area 7a show decreased visual responses for attended locations (Constantinidis and Steinmetz 2001; Steinmetz et al. 1994). In contrast, neurons in ventral visual areas show little or no attentional modulation when only one stimulus is presented.

Even in the presence of a distracting stimulus, neural responses in areas V2, V4, and IT are only strongly modulated by attention when the target and distractor lie in the same neuron’s receptive field (V2 and V4) (Luck et al. 1997; Moran and Desimone 1985; Reynolds et al. 1999) or in the same hemifield (IT) (Chelazzi et al. 1998). Recent studies have demonstrated that the degree of attentional facilitation in the dorsal and ventral stream depends on stimulus contrast. Attentional effects on the responses of MT (Martinez-Trujillo and Treue 2002) and V4 neurons (Reynolds et al. 2000) were significantly greater for low-contrast stimuli than for high-contrast stimuli.

The earliest difference that we observed between location matches and location nonmatches was a reduced early visual response for location matches. On these trials, the test stimulus appeared at the same location as the cue stimulus. A reduction of visual responses at previously cued locations has been found in neurons in the superior colliculus (Dorris et al. 2002; Robinson and Kertzman 1995), posterior parietal cortex (Constantinidis and Steinmetz 2001; Robinson et al. 1995; Steinmetz et al. 1994), and the inferior temporal cortex (Miller et al. 1991). These findings suggest that a reduction in visual activity for repeated stimulus presentations is a common response property of neurons in various cortical and subcortical areas. In some of these studies, this reduction has been interpreted as a neural correlate for an “inhibition of return” (IOR) (Posner et al. 1985). IOR refers to the increase in reaction times to stimuli that appear at previously attended locations. Indeed, behavioral experiments in monkeys have shown an IOR effect for stimulus-onset asynchronies comparable to those used in our experiment (Dorris et al. 1999). In our study, the saccade target appeared always at a previously cued location. Therefore our data do not address the question of whether the prefrontal cortex plays a role in the expression of IOR.

The attention effects that we observed in PFC neurons occurred 300–500 ms after test stimulus onset. By this time, the monkeys had already generated their saccades to match stimuli, which indicates that the differences between attended and nonattended stimuli occurred after the behaviorally critical task period. An enhancement late in the neuronal response for attended versus unattended stimuli has also been reported for V4 neurons with high contrast stimuli (Fries et al. 2001; Reynolds et al. 2000). Reynolds and colleagues (2000) found that the effects of attention on single low-contrast stimuli occurred early after stimulus onset (approximately 100 ms after stimulus onset), whereas the enhancement to high-contrast stimuli as in our study was only evident later in the response (approximately 200 ms after stimulus onset). The authors hypothesized that the strong inputs elicited during the initial transient response to a high-contrast stimulus delays any effects of attention until later in the response. For a low-contrast stimulus the afferent inputs are weaker and there often is not a strong transient response. This would allow the attention effects to be expressed at an earlier stage of the response. A recent study in V4 that used stimuli with a high local contrasts found an even later effect of attention (approximately 400 ms after stimulus onset) on neural firing rates (Fries et al. 2001).

It is possible that the appearance of a salient location nonmatch stimulus inside the neuron’s receptive field automatically drew attention away from the cued location. The late differences between attended and nonattended stimuli therefore may not be the result of sustained attention inside the receptive
field but may result from the shifting of attention away from the receptive field back to the cued location on location nonmatch trials. Our study, like other spatial cueing studies, cannot distinguish between these two diametrically opposite alternatives.

Another possibility for the late differences was that the monkeys already prepared for the generation of a saccade to the second test stimulus. This stimulus was always a match and would appear at the same location as the first test stimulus in the location match condition. The data, however, show that neural activity decreased back to baseline during the second delay period and there were no differences between the three nonmatch conditions. This indicates that the differences between location matches and nonmatches were indeed attentional modulations of the visual-related response and not neural correlates of the preparation for the subsequent saccade.

A recent study found strong responses to an attended target stimulus in PFC neurons that were effectively eliminated from stimulus onset when the same stimulus appeared at an unattended location (Everling et al. 2002). Here we did not find any evidence for an early filtering of visual responses by spatially focused attention. There are two main differences between the present task design and that of the previous study. In that study, stimuli were presented simultaneously in both hemifields and the target stimulus was the same throughout the experiment. In the present study, the target stimulus varied from trial-to-trial and only a single stimulus was presented in the left or right hemifield.

Electrophysiological recordings in V2 and V4 have shown that attending to a single stimulus in the neuron’s response field enhances, if at all, the neuron’s response. Two stimuli that compete in the neuron’s response field, however, often have opposing effects on responses. If a good and a poor stimulus are simultaneously presented in the neuron’s receptive field, attention to the good stimulus will elicit responses that are comparable to those elicited by the good stimulus alone. Attending to the poor stimulus, however, typically decreases responses to a level that is comparable to those elicited by the poor stimulus alone (Luck et al. 1997; Reynolds et al. 1999). These findings have been interpreted within the framework of a biased competition model of attention (Desimone and Duncan 1995). In this model, multiple stimuli compete for limited processing capacity and the selection process is biased by bottom-up and top-down processes. Accordingly, the single stimulus that appeared in our study at an unattended location were not filtered out because they did not compete with any other stimuli. In this case, attending away from the stimulus resulted only in a reduced discharge late in the response. It should be noted here that the effects for bilateral stimuli in the former study were observed for neurons with stimulus selectivity. Many of these neurons had response fields that included both hemifields (see Fig. 3c in Everling et al. 2002). It is therefore conceivable that the strong filtering that was observed in that study was the result of a competition of two stimuli in the large bilateral response field of these neurons (Rainer et al. 1998a). Indeed, many neurons that were location selective did not show these strong filtering affects (Everling and Duncan, unpublished observations).

While we found evidence for the effects of spatial attention on visual-related reponses of PFC neurons, we did not observe any effects of stimulus-related attention. This is in contrast with two other studies that found correlates of stimulus-related attention in the activity of PFC neurons (Everling et al. 2002; Rainer et al. 1998b). Rainer and colleagues (1998b) employed a “delayed-matching-to-sample” task with an array of three objects. Only one object was relevant for task performance and the monkey had to find this object and remember its location for the subsequent test period. An object served as a target for a block of 80 trials. The authors found that a large number of PFC neurons exhibited object selectivity in this task. This object selectivity, however, was a chronic change in the neuron’s activity, which presumably reflected its maintained memory across trials. The visual responses to good and poor stimuli seemed to be almost identical in that study after subtraction of the different baseline activity levels (Rainer et al. 1998b). In the present study, the target object varied from trial-to-trial so that our task did not require any memory maintenance across trials.

In another study, Everling et al. (2002) found that PFC neurons discriminated between target and nontarget stimuli at attended locations even when just a single stimulus was presented. Here we found no difference in the response to a preferred stimulus between trials when it was a target and those when it was a nontarget. The major difference between the studies was that one stimulus was a target and two were always nontargets throughout the previous study (Everling et al. 2002). The long training period on this target/nontarget discrimination may have resulted in a form of experienced-dependent plasticity similar to what had been observed in frontal eye field neurons (Bichot et al. 1996).

In conclusion, our data demonstrate effects of spatial attention but not stimulus-related attention on the activity of PFC neurons. The results also clearly show that even a behaviorally irrelevant stimulus is initially represented in the activity of those neurons when it does not have to compete with another stimulus.

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