Visual Responses in FEF, Unlike V1, Primarily Reflect When the Visual Context Renders a Receptive Field Salient

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The Frontal Eye Field (FEF) is part of the prefrontal cortex that modulates our attention and helps us funnel our resources toward important changes in our visual environment. In previous studies the FEF was shown to have a meaningful role in spatial attention and saccadic eye movements. However, as study of the Frontal Eye Field has continued, descriptions of the FEF as a attentional modulation mechanism have shifted the view of the FEF from its role in saccades as a purely motor structure to a more complex higher level cortical processing region. In reconsidering the function of the FEF, its role in the control of saccades may just one manifestation of a broader role in the control of visual attention, which encompasses both overt attention (with visual attention centered around the receptive field) and covert attention (with visual attention also attending to the surrounding areas). This may bridge the dialectic between these two functions, showing that its role in covert attention to outside stimuli may modulate attentional shifts with saccades.

The FEF has a decisive role as a salience map for visual stimuli independent of its role in motor functions. FEF is most closely related to covert attention, and the activity of neurons in the FEF thought to be correlated with the focus of the monkey's visual attention, even in the absence of saccades. Single-neuron recordings of the FEF neurons display a significant modulation in firing rates associated with the spatial location for covert attention (seen in previous research, Thompson et al., 2005). The FEF contains neurons with latency sensory responses and it able to quickly shift our attention to relevant stimuli.

On the groundwork of stimulation, recording, and inactivation experiments, the FEF appears to play a significant role in the planning and execution of saccadic eye movements in line with other frontal cortex regions. Similar experiments have also recently demonstrated that the FEF participates in the control of visual selective attention. This article focuses primarily on the FEF as studied in macaque monkeys (although it bridges to its homologues in other species, including humans, it is thought to function quite similarly) . This article is iconic for setting the stage for future directions of FEF circuitry research.

Methods: In this task, macaque monkeys fixated on a screen, while awake, head fixed to the screen azimuth. Macaque were reinforced with juice reward for fixating for this task. Recording were taken using a metal electrode in FEF or V1, they measure some population (almost at random) and the experimenters did not distinguish recordings by cell type.

V1 is simple, when it sees a stimulus that matches preference for an orientation and size, it just fires to stimuli in its receptive field. The FEF is more complex, modulation in attention, and right before saccades receptive field shifts. Joiner et. al question whether the visual brain cares

about the “surprising-ness” of a stimuli (is it salient?) and also whether stimuli in and outside of the receptive field are important. The first figure explains that V1 may not “surprising-ness” encoded, but FEF does encode for that.

Salience is defined simply as anything that grabs your attention, an exogenous form of attention. This article does not necessarily study attention rather the effect of visual surprise in FEF and V1 is studied in primate models. This provides a unique insight about the role of FEF, timing determines salience and changes in temporal pattern, like the change from 1, 2, 3, 4, 1 to 1, 2, 3, 1,1 in music tempo may effect our response to attending to the stimuli. Later discussed, an attentional blink in the receptive field before in short ISI condition may create a reduced response.

The macaque monkey fixates on cross while a FEF neuron is recorded; during this fixation they simultaneously map receptive fields of FEF cells during fixation. A stimuli grid, hidden from monkey, contained fixed stimuli location inside of receptive fielding outside of it. Flashes then randomly appear in any of these locations sequentially- one appears inside receptive field, whilst others are close or further. To measure the effects of salience- a slow versus fast pattern was presented after which the flash appear in the receptive field.

For the slow, long inter flash time, it is predicted that each flash is salient- thus it captures covert attention for increased ISI intervals . The data also ignores the long inter-flash time between when the same stimuli may be presented. No flash should be salient for the short timing (less salient, more like white noise). In trials for neuron response, analyze data for flash appearing in the receptive field for both conditions. The data for fast inter flash time is different, and if it’s in the receptive field twice or more, you could have a condition with receptive field field being stimulating multiple trials. Experimenters may have attempted to prevent flash from occurring too many times in the same place during these trials. They also increased the probability of a blank flash for the short ISI condition so it could be easier to directly compare to the long ISI condition.

Figure 1:
In condition 1, figure 1A, there is a long inter flash time of 500 ms for each stimuli (presented for 100 ms in both conditions). In condition 2, figure 1B, there is a short inter flash time of only 16ms between stimuli. In trials with 16 ms, there is no response of outside of the receptive field that should be consciously perceptible (also it is not possible to follow dots in condition 2, it may be more similar to white noise). The seven colors at the top of the figure correspond to flash position with regard to the receptive field. In figure 1A, the long inter trial times, show strong responses to stimuli within their receptive field. In figure 1B, with shorter inter trial times, there is less of response, even in the center of the receptive field. Figure 1B is near random except for red, which is odd considering the visual stimuli should stimulate the same neuron. The response in A and B very different, and is not explained by surround suppression considering that receptive field abnormalities are taken into account in C.

In B there is difference of response, less than 10 spikes/sec in the non salient condition. This suggests the FEF is informed of all the receptive fields, not just the simple V1 magnification. In figure 1C the firing rate is shown as function of flash position, neuron preferred flash position minus 7 degrees and rarely fire outside of that range for either condition. The firing rate in the salient, long ISI condition, is higher and they has relatively large receptive field, in non salient condition.

In D, the data is transformed from C and plotted on different axises. This contrasts firing in long vs short, closer to center means less change in short condition
The same neuron in C and D, the FEF has a low slope, ~0.13, suggesting it may not react to receptive field responses, and most responses are due to salience. A slope of 0 suggests all salience, whereas a slope of 1 suggest a stronger response to the visual stimuli. The short ISI condition, as presented in 1D, is significantly effected by salience.

Figure 2:
This figure plots slope of each of neurons in FEF and V1, the high R value means theres is a better fit for the correlation between it's response and slope (the amount it responds to salience vs visual activity. In FEF the mean corresponds to about 20% responding to salience, 80% to stimuli in receptive field. For the FEF neuron fit is not good for some of them, worst fit cells have 0 slope for all salience.In V1, slope is close to 1, the fit is consistent and significant, suggesting cells have a strong response to stimuli their receptive field.

Figure 3:
This is analogous to the figure 1, but instead this measures the response in V1 for each condition. V1 responds similarly to condition 1 and 2 (to the horizontal bars shown, above to stimulate each receptive field). V1 neuron only looks at receptive field, not strongly modulating the response, thus there is not a significant change in firing rate for the V1 between the conditions as shown in C and D. V1 doesn't different differentiate between short and long ISI stimuli, but other areas like FEF may respond to salient stimuli.

Each position point is shown with the black and open circles. In these example neurons, it has a slope of 0.96 for V1, proving they are only responding to stimuli in receptive field. The effect of salience is not as large for stimuli closer to receptive field, and the decrease of salience does not produce a significant effect.

Figure 4:
Mayo and Sommer (2008) found that when ISI is large, around 400 ms, the response was similar to when the stimuli was presented alone. Very fast stimuli allows for local adaption. The random sequence of short ISI in their experiment lets this experiment differentiate between the effects of salience versus local visual adaption. Figure 4 shows the difference between the FEF and V1 for the time until stimuli is shown in receptive field (for presentation of blanks or blanks and stimuli).

The trials show shorter intervals for the time until a stimuli is presented in the receptive field. For this figure, the firing rate was mined from previous random trials. For each it was divided by rate for condition 1, the long ISI condition, so the data could be normalized.
For the FEF neurons there is a reduction down to 40% of spiking response in short ISI condition. The mining of condition 2 data showed that for shorter intervals that have time before the flash with nothing in receptive field there is less of a response for the short ISI. This plots the effect of salience, amount response gets reduced, but response doesn't change in V1 cell.
100 ms before the stimuli presented there was no difference V1, there was only a reduction in response when it previously stimulated 100-300ms before. There is also no backward masking for FEF response. A blank or not a blank right before it responded had little effect on short ISI responses. In FEF there was a small (perhaps insignificant) gradual increase in response as the series of blanks (before the receptive field stimuli) increased (up to 300ms).

The open circles indicate no stimulation anywhere on screen. When they measured to response to the flash in the receptive field (with blanks beforehand), and compared it to response with no flash in receptive field for condition 2, with a delay of 200-300 ms there was a very small increase in response to the first RF flash in FEF. Some flashes are more salient with different time delays, but the effect is less strong with previous flashes and less so V1 (more of an effect FEF). In V1, theres is some effect of local salience for longer intervals between flashes. There's a small increase for delays up to 300 ms in V1, but it's much more prominent in FEF. This effect could also be insignificant since they had small sample sizes (15 and 28 neurons were tested in V1 and FEF, respectively).

Figure 5:
The thick grey line is control, a subset of their data (analyzes shorter windows for same 28 neurons tested before). This shows PSTH of the responses for only FEF neurons. For FEF in condition 1, grey is a subsample, with the biggest response every trial. Red represents a flash in receptive field in condition 2, following each stimuli conditions (0-500ms before). All other colors (not grey and black) are a subset of red.

The magenta vs black is also shown figure 1, with short ISI conditions producing less firing in the FEF. Each color shows timing with no stimulation in receptive field before for each respective time period. This predicts when the salience effect comes online during the neuron's response. The response to all conditions in 2 is lower but highest for magenta, allowing 500 ms until there is a flash receptive field. The salience effect is lessened for the short ISI condition.

Figure B compares these conditions to the black line (the long ISI condition), the point at which the curves diverge may help determine the effect the salience has. If you look at difference 300 ms (blue) vs 500 ms (magenta) for condition 2 flashes in receptive field, they diverge at roughly the same time. Grey and black lines- condition 1 neurons steadily increase in response latency but the neurons to respond more earlier to flash in non salient condition (when cyan, blue and

magenta appear above the grey and black line, this may be due to the random population of neurons selected or other measuring errors). The firing rate is lower in salient condition as compared non salient task.

In figure C at 50-60ms blue and magenta diverge from the black line. The black dashed line represents the control, they compare that to the onset latency of each cell (with absolute latency). There is a relationship for absolute latency and time that they diverge. The absolute latency measures the time to half max for a spike. The point at which the firing rate goes up for the salient stimulus, shows when the salience effect "kicks in". At 50 ms in figure A is there is a clear difference in the latency, slower latency then divergence point is reached later. This figure takes that into account when you measure separation time. The separation happens soon after the onset, separation time is similar to 300 ms and 500 ms, salience effect comes online shortly after response latency. There is a larger response in FEF to the more salient stimuli and less response when the RF stimuli was presented after random stimuli were flashed (even outside of the receptive field).

Extra Comments:

The effect seen in V1, although small with 0.96 responding to visual stimuli in the short ISI condition, may lead to the conclusion that in the short ISI there is some feedback (indirectly) from FEF to V1. Also in FEF there may be an effect from LIP and other attention regulation areas, leading to the pop out effect of a single visual stimuli when it is presented alone after some time period. In line with the results of lesion studies, unilateral pharmacological inactivation of the FEF leads to spatially specific contralateral reaction time deficits in a visual search task, even when the monkey abstains from eye movements during the search (Wardak et al., 2006). Some of the most compelling data to support the role of the FEF in attention, show increased activity in the FEF is causally related to the focus of spatial attention, then generating activity in the FEF through stimulation should produce spatially specific attention-like effects on behavior and physiology. Moore and Fallah (2004) electrically stimulated FEF sites of monkeys performing a change detection task. Change detection tasks measure the influence of selective attention on visual perception. Trying to detect a change in a dynamic display like the one tested in this experiment can be difficult, but knowing there will a change in the receptive field position may allow them to be better at this task (Rensink, 2002). Perhaps since the monkeys could predict there is a visual change in the receptive field location they could have more of a response to changes, thus perhaps allowing them to have an attentional blink when the the stimuli were presented in rapid succession- leading to reduction of response shown for the short ISI condition.