Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006



# Spatial frequency modulates the human visual cortical response to temporal frequency variation: an fMRI study

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*Abstract*— **The brain response to temporal frequencies (TF) has been already reported, but with no study for different TFs with respect to various spatial frequencies (SF). Functional Magnetic Resonance Imaging (fMRI) experiments were performed by 1.5 Tesla General Electric-system in 14 volunteers (9 males and 5 females, range 19-26 years) during square-wave reversal checkerboard visual stimulation with different temporal frequencies of 4, 6, 8 and 10 Hz in two states of low SF of 0.5 and high SF of 8 cpd (cycles/degree). The activation map was created using the data obtained from the block designed fMRI study. Pixels whose correlation coefficient value was above a threshold of 0.33, in significant level P <0.01 were considered activated. The average percentage BOLD (blood oxygenation level dependent) signal change for all activated pixels within the occipital lobe, multiplied by the total number of activated pixels within the occipital lobe, was used as the criterion for the strength of the fMRI signal at each state of TF& SF. The results demonstrated that the strength of the fMRI signal in response to different TFs was maximum in 6Hz for high SF of 8cpd, while it was maximum at TF of 8Hz for low SF of 0.5cpd. The results of this study agree with the results of animal invasive neurophysiological studies showing spatial and temporal frequency selectivity of neurons in visual cortical areas. These results can be useful for vision therapy (such as the treatment of Amblyopia) and selecting visual task in fMRI studies.**

## INTRODUCTION

THE image received on the retina is just a particularly pattern of different light intensities and wavelengths which may change from moment to moment. These changes, either spatial and/or temporal in the image pattern provide the major information available for visual processing [1]-[2]. The information associated with the coarser patterns is reflected by low spatial frequencies (LSF) and those with finer patterns mirror high spatial frequencies (HSF) [3]. Most visual scenes present both temporal and spatial information. Temporal changes per se are important in edge detection as in the case of stationary flickering lights. Temporal frequency (TF) is the rate at which luminance changes occur in the image [2].

Although the human brain response variation with a wide range of TFs has already been reported [4]-[6], there is no imaging study regarding different TFs with respect to various SFs.

Fox and co-workers [4] studied the stimulus rate dependence of regional cerebral blood flow (rCBF) in human striate cortex by Positron Emission Tomography (PET). The results showed that the rCBF response peaked at a temporal frequency of 7.8 Hz and then declined. Mentis *et al* [5] investigated the rCBF response to frequency variation of pattern-flash visual stimulus employing PET scan. They found an rCBF response in the striate cortex with a peak at 7 Hz. Kwong and colleagues [6] investigated the stimulation frequency effect on visual cortex activation assessed by functional magnetic resonance imaging (fMRI). Their findings agreed with the previous positron emission tomography observations and showed that the largest MR signal response occurred at 8 Hz. Similarly Thomas and co-workers [7] showed that fMRI signal also peaks at a flicker frequency of 8 Hz. Ozus *et al* [8] studied the rate dependence of human visual cortical activation following brief stimulations. They found that BOLD signal change increases up to a stimulus frequency of 6 Hz and then remains nearly constant.

In neurophysiological studies [9]-[12], it has been suggested that there are multiple visual channels tuned to each of the SF bands and there exists spatial and temporal frequency selectivity in neurons of the visual cortex. Additionally, various psychological studies [13]-[17] support these results.

The purpose of this study has been to evaluate the visual cortex activity response to TF variations with different SFs.

## I. SUBJECTS AND METHODS

### *A. Subjects*

The subjects were 14 right-handed healthy volunteers (9 males and 5 females, range 19-26 years; mean age ± S.D = 22.4 ± 1.8). All subjects had normal visual acuity of 20/20 in both eyes based on snellen's chart examination, good binocular vision based on cover test and fly Titmus stereo acuity test results, and normal visual field assessed by confrontation test. There was no history of visual or other neurological problems in any subject. The volunteers gave

This study was financially supported by the Research Center for Science and Technology in Medicine (RCSTIM) and Research Division of Tehran University of Medical Sciences, Tehran, Iran.

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written informed consent to participate in this study

### B. Visual Stimuli

We employed square-wave reversal checkerboard visual stimulation with different temporal frequencies of 4, 6, 8 and 10 Hz in two states of low SF of 0.5 and high SF of 8 cpd. Visual tasks were provided by Presentation Software version 0.60 and projected by a video projector on a screen in front of MRI table. The subjects could see the visual stimuli through the non-magnetic mirror in front of their eyes during image acquisition. The MRI room as dark as possible; therefore, the visual tasks were the only visual stimulation the subject could see. The mean luminance of the entire checkerboard was 161.4 cd/$m^2$ and the black and white check contrast was 96%. The visual angle of the stimulus subtended 11.2 degree horizontally and 8.3 degree vertically.

### C. Data Acquisition

Functional images obtained with a GE 1.5 T MRI system equipped with echo-planar (EPI) acquisition (TR = 3000 ms, TE = 60 ms, flip angle = 90˚, matrix size = 64×64, number of slices = 11, FOV = 220 × 220 $mm^2$, voxel size = 3.44×3.44×4.0$mm^3$) sensitive to BOLD contrast. Activation period was “on” for 18 sec and “off” for 18 sec in the rest period, i.e., 36-sec cyclic block design. Different spatial and temporal frequencies were presented over 2.5 cycles for a total duration of 1.5 min per trial. The functional images were obtained in an axial orientation parallel to the anterior commissure-posterior commissure (AC-PC) line. A functional volume composed of 11 slices with thickness of 4 mm and spacing of 1 mm was scanned for 45 times in each trial. An anatomical whole brain image corresponding to functional image was also obtained ($T_1$-weighted, TR = 400 ms, TE = 10 ms, flip angle = 90˚, matrix size = 256×256, number of slices = 27, voxel size = 0.86 × 0.86 ×4.0 $mm^{3)}$ for each subject.

### D. Data Analysis

Analysis was carried out using FEAT (FMRI Expert Analysis Tool) Version 5.4, part of FSL (FMRIB’s Software Library, www.fmrib.ox.ac.uk/fsl). The following pre-statistics processing was applied; motion correction using MCFLIRT [18]; non-brain removal using BET [19]; spatial smoothing using a Gaussian kernel of FWHM 5 mm; mean-based intensity normalization of all volumes by the same factor; high pass temporal filtering (Gaussian-weighted LSF straight line fitting, with sigma=50.0s) Time series statistical analysis was carried out using FILM with local autocorrelation correction [20]. Z (Gaussianised T/F) statistic images were thresholded using clusters determined by Z > 3 and a (corrected) cluster significance threshold of P=0.05 [21]. Using MRIcro (http://www.mricro.com/), The activation maps including activated Pixels whose Z value was above a threshold of 3, in significant level P=0.05 were superimposed on corresponding $T_1$-weighted anatomical images. The average percentage BOLD signal change for all activated pixels within the occipital lobe, multiplied by the total number of activated pixels within the occipital lobe, was used as the criterion for the strength of the fMRI signal at each state of TF& SF. These values were normalized to their largest value.

## II. RESULTS

The results show that strength of the fMRI signal changes with TF variations of visual stimulation. The maximum strength of the fMRI signal occurs at a TF of 8 Hz for visual stimuli with SF of 0.50 cpd and in TF of 6 Hz for stimuli with SF of 8 cpd (ANOVA, $p < 0.005$). For all TFs but 4 Hz, the strength of the fMRI signal in high SF is significantly lower than that of fMRI signal in low SF (t-test, $p < 0.01$).

The functional visual maps in the maximum BOLD response to TF of 8 Hz in SF of 0.5 cpd and to TF of 6 Hz in SF of 8 cpd were superimposed onto the correspond-ding $T_1$-weighted anatomical images for one of the subjects, is shown in figure 1.

The average fMRI signal strength for fourteen-subjects as a function of TF for two different SF of 0.50 cpd and 8 cpd is depicted in figure 2. For LSF, the strength of the fMRI signal increases gradually with the TF, reaching a maximum in the 8 Hz and then decreases, whereas for HSF, the signal strength reaches a peak at 6 Hz and then decreases.

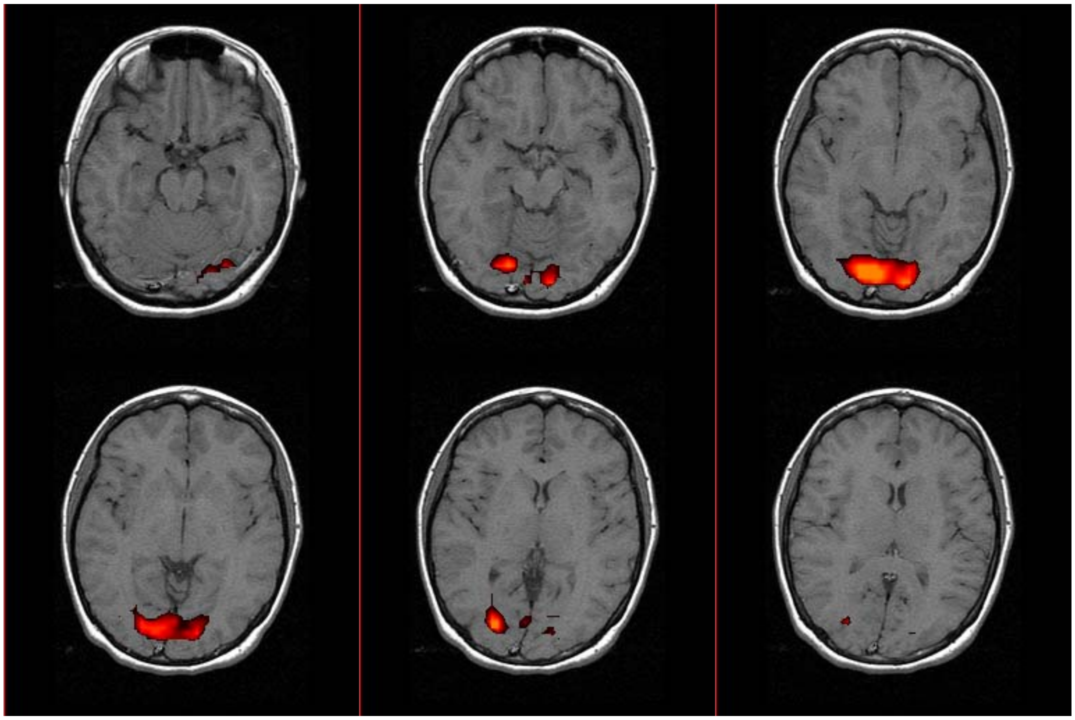
## III. DISCUSSION

This study shows that in low SF of 0.50 cpd, the maximum BOLD signal change occurs in TF of 8 Hz and this result is consistent with many previous reports during light-flash stimulations [4]-[7] or reversal checkerboards of low SF [22].

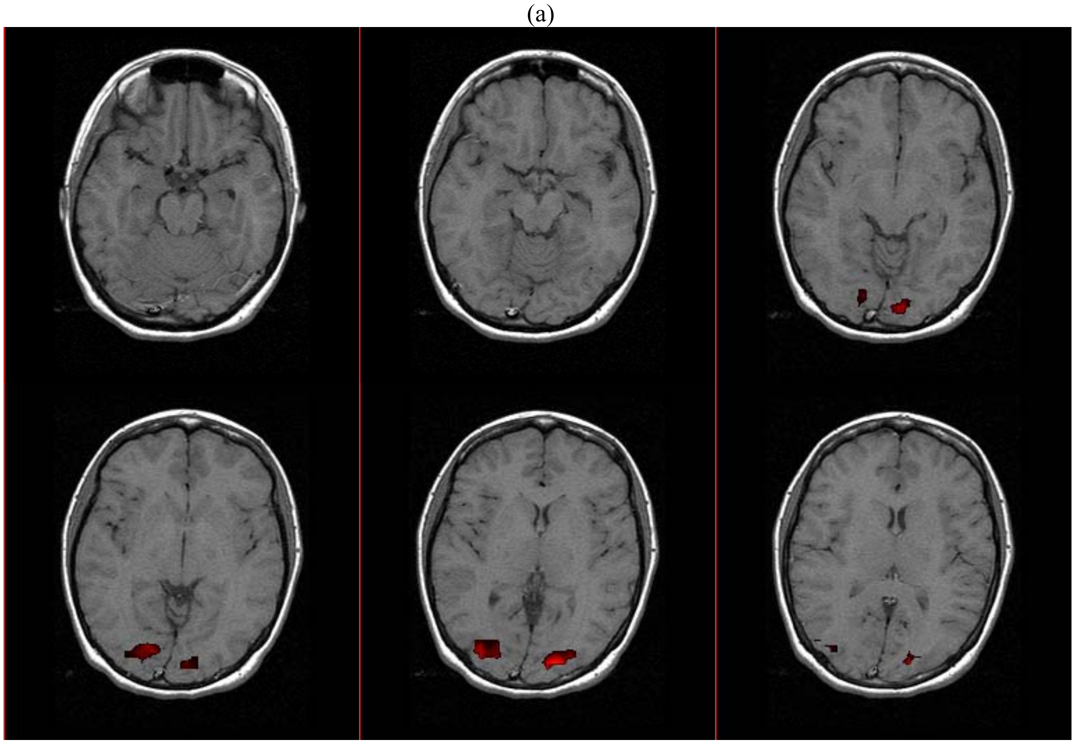
On the other hand, the strength of the fMRI signal in response to temporal frequency variation is different for various spatial frequencies, i.e., the amplitude of the fMRI response at different temporal frequencies is significantly dependent on spatial frequency components of the visual stimuli (i.e.; Checkerboard).

The results of the current study are in agreement with those of invasive neurophysiological studies in animals [9]-[12] that show spatial and temporal frequency selectivity of neurons in the visual cortical areas. In this study, at high SF of 8 cpd, the maximum BOLD signal was produced in the TF lower than 8 Hz, i.e., in 6 Hz; this could be explained on the basis of the concepts of *sustained neural channel* (high SFs associated with lower TFs) and *transient neural channel* (low SFs associated with higher TFs) [23].

The fact that the higher the velocity (or TF) the lower the SFs to which the cortical visual cell is tuned [24] justifies the finding of the present study, i.e., with increasing TF from 6 to 8 Hz, those cells responding to SF of 8 cpd show a pronounced reduction in response to that SF and result in a decrease in BOLD signal.



(a)



(b)

Zstat range: 3.0 10.0

Figure 1: Comparison of activation area with the maximum response at temporal frequency of 8 Hz in LSF of 0.5 cpd (a), and 6 Hz in HSF of 8 cpd (b) for one of subjects. (six slices of total eleven slices)

According to psychophysical and psychological studies [13]-[17], it has been suggested that visual perception is mainly based on spatial frequency (Fourier) analysis of the image. This analysis starts with processing LSFs, followed by processing HSFs. Therefore spatial frequency is an important factor in evaluation of responses of the visual cortex to physical and psychophysical aspects of vision such as temporal frequency.

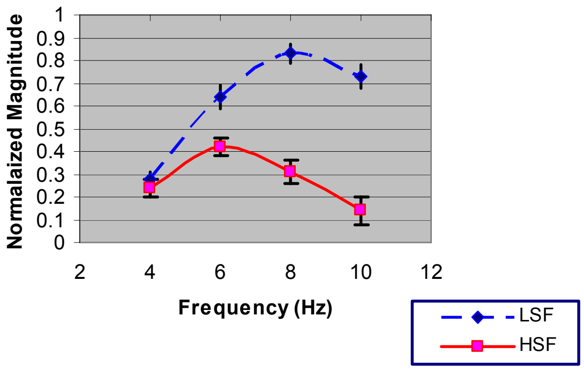



Figure 2: Comparison of the fourteen-subject averaged fMRI signal strengths as a function of TF in two different SFs of 0.5 cpd 8 cpd. (The signal has been normalized to its largest value and the error bars representing the standard error of mean)

## I. CONCLUSION

The results of this study provide an optimum TF for different SFs in the visual tasks employed in functional visual imaging. These results could be beneficial in various methods of vision therapy and clinical visual treatments of conditions such as amblyopia.


## ACKNOWLEDGMENT

We would like to thank Behrooz Rafiei, Ahmad Lavasani and Ali Mahdavi for their cooperation at the medical imaging center of Imam Khomeini Hospital. This study was financially supported by the Research Center for Science and Technology in Medicine (RCSTIM) and Research Division of Tehran University of Medical Sciences, Tehran, Iran.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