THE ROLE OF CONTRAST AND SIZE IN MOTION PERCEPTION: BEHAVIORAL AND NEUROIMAGING STUDY OF CENTER-SURROUND INTERACTIONS IN PRIMARY VISUAL CORTEX (V1) AND MIDDLE TEMPORAL AREA (MT+)

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THE ROLE OF CONTRAST AND SIZE IN MOTION PERCEPTION: BEHAVIORAL AND NEUROIMAGING STUDY OF CENTER-SURROUND INTERACTIONS IN PRIMARY VISUAL CORTEX (V1) AND MIDDLE TEMPORAL AREA (MT+)
By GÖRKEM ER
September 2018

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

THE ROLE OF CONTRAST AND SIZE IN MOTION PERCEPTION: BEHAVIORAL AND NEUROIMAGING STUDY OF CENTER-SURROUND INTERACTIONS IN PRIMARY VISUAL CORTEX (V1) AND MIDDLE TEMPORAL AREA (MT+)

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Behavioral experiments have demonstrated that observers' ability to discriminate the drift direction of a grating improves as its size increases if the grating has a low contrast, and deteriorates if it has a high contrast [1]. It has been proposed that receptive field organization in middle temporal (MT+) visual area underlies this counter-intuitive perceptual effect. Supporting evidence for this proposal has been provided in literature [2]. However, previous studies have not unequivocally showed that MT+ is the sole area whose activity underlies the perceptual effect.

Here, we investigate the activity patterns of primary visual cortex (V1) and middle temporal (MT+) in response to drifting Gabor patches in differing size and contrast levels to elucidate the neural region involved in size-contrast interaction in motion perception. We first replicated the findings in the literature with a behavioral experiment, where small or large (1.67 and 8.05 degrees of visual angle) drifting gratings with either low (2%) or high (99%) contrast levels were presented at the periphery (centered 9.06 degrees of visual angle to left and right of fixation). We measured the duration thresholds (79%) for accurately discriminating the drift direction of gratings for eleven participants using an adaptive staircase and two-alternative forced choice (2AFC) design. In line with previous literature, we observed that increasing the size of the low-contrast stimuli resulted in decreased discrimination threshold, while for high-contrast stimuli, increasing the size resulted in increased discrimination threshold.

In the second stage of the study, six observers participated in a block design fMRI study with the same spatial configuration and contrast levels used in the

behavioral experiment. We first identified the region of interests (ROI) for visual area V1 and MT+ separately for all participants. Then, we identified a "sub-ROI" that corresponds to the region that was selectively responsive to the small sized stimuli (1.67 degrees) using an independent localizer. With this setup, we allowed for both large and small sized gratings to stimulate the sub-ROI throughout the entire scan. Therefore, changes in Blood Oxygenated Level Dependent (BOLD) response at the sub-ROI in response to large compared to small sized gratings indicated the influence of the surrounding region to the center of the gratings. In area MT+, we observed that increasing the size of the grating increases the BOLD activity if the stimuli have low contrast, compared to high contrast. In other words, surrounding region had a facilitative influence to the group of MT+ neurons encoding the center of the stimuli if the stimuli had low contrast. This neuronal facilitation observed with the neuroimaging data explain the enhancement of the performance with increasing the size of the low-contrasted stimuli observed at the behavioral experiment. In V1, however, increasing the size of the high-contrasted gratings increased the BOLD activity, compared to activity evoked by increasing the size of the low-contrasted gratings. On the whole, we show that center-surround interaction in V1 and MT were differentiated in response to peripherally viewed drifting Gabor patches at differing contrast and size levels, hence we provide further evidence that the perceptual size-contrast interaction effect is likely to originates at cortical area MT+.

Keywords: Visual motion; spatial suppression; surround suppression; surround facilitation; primary visual cortex; middle temporal region; contrast; size.

ÖZET

KONTRAST VE BÜYUKLÜGÜN HAREKET ALGISINDAKI ROLÜ: KORTIKAL BÖLGE V1 VE MT'DEKI ÇEVRE VE MERKEZ ETKILEŞIMLERININ FMRI VE DAVRANIŞŞAL DENEYLERLE INCELENMESI.

GÖRKEM ER
Nörobilim, Yüksek Lisans
Tez Danışmanı: Hüseyin Boyacı
Eylül 2018

Davranışşal deneyler, izleyicinin hareket eden görsel uyaranın yönünü tayin etme becerisinin uyaranın boyutunun büyümesiyle attığını, fakat bu artışın uyarıcı düsük kontrasta sahipse gerçekleştiğini, yüksek kontrasta sahipse de yönü tayin etme becerisinin düştüğünü göstermiştir [1]. Kortikal bölge "orta temporal" (MT+) deki nöronlarının alım alanı organizasyonunun bu gözlemlenen konrast-büyüklük etkileşiminden kaynaklanan algı etkisine sebep olduğu ileri sürülmüstür. Bu önermeyi destekeyen deliller de temin edilmiştirdir literatürde [2]. Fakat daha önceki araştırmalar, MT bölgesinin aktivitesinin bahsedilen algısal etkiye yol açan tek sorumlu bölge olduğunu kesin bir şekilde test edip göstermemiştir.

Bu araştırmada, hareket algısında büyüklük-kontrast etkileşimini işleyen bölgeyi bulmak amaçlanmaktadır. Bu sebeple, görsel korteks (V1) ve MT+'nin aktivite grafiklerinin algısal sonuçlara olan rolünü incelenmektedir. İlk olarak, davranışşsal deneylerle küçük ve büyük (1.67 ve 8.05 derece) boyutlarda hareket eden ve düşük (% 2) veya yüksek (% 99) kontrast seviyesinde Gaborları cevresel bölgede (fiksasyon bölgesine uzaklık sağdan ve soldan 8.02 derece) göstererek literatürdeki sonuçları doğrulayan sonuçları bulduk. Hareket yönünün doğru ayırt edildiğini gösteren eşik değerleri (% 79) iki-alternatif zorunlu seçenek (2AFC) tasarımı ile on bir kişi için ölcüldü. Daha önceki araştırma sonucları ile örtüşerek, hareket yönünü doğru ayırt eden eşik değerinin uyarıcı düşük kontrasta sahipken uyarıcının büyüklüğünün artmasıyla azaldığını; yüksek kontrastlıyken ise, uyarıcının büyüklüğünün artmasıyla birlikte arttırdığını gözlemledik.

Araştırmanın ikinci aşamasında altı katılımcı, davranışşsal deneydeki uzaysal ve kontrast seviyelerin aynı tutulduğu blok tasarımlı fMRI arastırmasına katıldı. Biz ilk olarak her katılımcı için, yer-belirleme çekimleri ile V1 ve MT+ bölgelerini temsil eden ilgi alanları (ROI) belirledik. Daha sonra, bu bölgeler içerisinde bağımsız bir 'yer belirleme' (localizer) ile küçük boyutta (1.06 derece) uyarıcıyı işleyen 'alt bölge' (sub-ROI) belirledik. Bu kurgu sayesinde, büyük ve küçük boyuttaki uyarıcıların bütün çekim boyunca altbölgeyi uyarmasına izin verdik. Bu sayede, alt bölgede gözlemlenen fMRI aktivitesi değişikliği çevrenin merkeze olan etkisini ön plana çıkaracaktı. Uyarıcının merkezine verilen MT+ aktivitesinin çevresel bölge düşük kontrasta sahipken arttığını, yüksek kontrasta sahipken değişmediğini gözlemledik. Bununla birikte, uyarıcının merkezine verilen V1 aktivitesininin çevresel bölge yüksek kontrasta sahip olduğunda arttığını, düşük kontrasta sahipken değişmediğini gözlemledik. Diğer bir deyişle, uyarıcı düşük kontrasta sahip olduğunda, çevresel bölgenin merkezi işleyen MT+ nöronlarına etkisinin destekleyici (facilitative) olduğunu gözlemledik. Bu nöronal iyileşme (neural facilitation) davranışşsal deneydeki düşük kontrastlı uyarıcının büyüklüğünün artmasıyla gözlemlenen performans artışını açıklar niteliktedir. Bu sonuçlar, merkez-çevre etkileşiminin V1 ve MT+ bölgeleri için ayrıştığını, büyüklük-kontrast etkileşiminin MT+ bölgesinde başladığına delil göstermektedir.

Anahtar sözcükler: Görsel hareket, uzamsal baskılama, çevresel bastırma, çevresel destekleme, açıklık, saptama, tanımlama, eşik, görünüm.

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Chapter 1

Introduction

1.1 Visual Information Flow Within the Brain

The first interaction between the light rays from the external world and the human nervous system starts at the surface of the retina. As we are moving in the world light arrays hit the retina, where numerous photo receptors are readily waiting for transduction of the light energy into the currency of the nervous system - the electrical energy. Following a cascade of events mediated by Bipolar cells, Horizontal cells and Amacrine cells (referred collectively as interneurons), the output then become myelinated and sent off to the sub-cortical areas via the optic nerve formed by the retinal ganglion cells [3]. Retinal ganglion cells' spiking activity evoked by the visual stimuli within the neuron's receptive field -the extend in which photoreceptors and interneurons modulate the retinal ganglion cells' activity, is found to be modulated by the sum of the activity evoked by the neighboring visual stimuli. This is called antagonistic center-surround organization of the receptive field. Although some cells encode the changes in the overall luminance in the visual field, thus, responsible for controlling the pupillary reflexes, majority of the ganglion cells have center-surround organization of receptive field. There are two distinct class of retinal ganglion cells: on-center, off-surround ganglion neurons depolarize (excited) when the light hits the center of their receptive field,

while the light hitting the surround triggers an inhibitory mechanism for the center (off-surround). The other class, the off-center, on-surround ganglion neurons embody the opposite organization, where light hitting the surround excites the neuron, and light that hits the center inhibits. To put it differently, off-center neurons get excited as the light hitting the center disappears (some refer this as a rebound). The output, then, diverges at what is called optic chiasm, where some portion of the signal coming from the eye sent sent to brain areas in the contralatereal hemisphere, while the rest is kept at the ipsilateral region [3].

Pretectum, the superior colliculus, the lateral geniculate nucleus (LGN) are the main relay stations for the flow of the visual information after the eye, where the output received from the retina are pre-processed and relayed to the higher level regions for more complex visual processing. LGN is the main terminal for 90% of the incoming signals relayed at there. Its six distinct layers are defined and structured by the type of cells it embodies [4]. Cells that have relatively larger cell bodies and extensive dendritic connections are called Magnocellular cells (M-Cells), and they are located at the inner two layers (the most ventral layers) of the six layered LGN. M-cells are reported to have associations with motion discrimination processing, increased sensitivity to temporal frequency and lowered sensitivity to spatial frequency [5]. Parvocellular cells (P-cells), on the other, are located dorsal (outer four) layers of the LGN, and embody relatively smaller cell bodies, relatively lesser dendritic arbitration and portray increased luminance sensitivity, and color contrast, high sensitivity to spatial frequency, and low sensitivity to temporal frequency [6]. Research show that P-cells are associated with coding spatial structure, color, and the form of the image, hence provide high spatial resolution to the nervous system [3]. Similarly to retinal ganglion cells, in their seminal work Hubel & Wiesel revealed that lateral genuculate neurons also have antagonistic center-surround receptive field organization [7].

Majority of the accumulated output from the LGN is sent to the cortical region located at the far back of the cortex, namely layer IV of the primary visual cortex (V1). Like the LGN, here too each hemisphere receives and process signal that are coming from the contralateral visual field. Due to the relative ease of applying measurement methods, and the convenience for observing the effect of the

experimental manipulation, V1 is one of the most researched areas in the brain. Spatial properties of the visual field are mapped very neatly and organized on to the primary visual cortex, in which upper half of the visual field is represented at the lower bank of the calcarine sulcus (the anatomical landmark of the primary visual cortex, a deep fissure that divides the the primary visual cortex), while the lower half of the visual field is processed at the upper bank of the calcarine sulcus at each hemisphere. This organization of each neurons being responsible from a distinct region in the visual field, and the neighboring neurons encoding the neighboring visual field locations is called retinotopic organization. Another major characteristic of the V1 region is what is called cortical magnification, in which the center of the gaze (the visual field that corresponds to the fovea) is magnified and represented more, compared to representation of the non-foveal visual areas. Fundamental visual codings are done at this stage as there are distinct sub-groups of neurons that are responsive to orientation selectivity, form, moving direction at a specific speed and stimulus length [3]. Spatial and temporal variations in the signals of V1 neurons encode the relative locations of the objects, motion, orientation and shape [8, 9, 10]. V1 neurons, then, send to their signals to the higher cortical regions for more complex processing to be done.

Visual information from V1 is transmitted to the higher cortical regions in not necessarily mutually exclusive, but largely distinct two pathways: the pathway that is ventral of the other pathway is defined as the 'what' pathway, ranging from V1 to temporal lobe via what is called V4 region, and the dorsal pathway which is mainly referred as the path from V1 to V5 (MT) up until parietal lobe via passing through V2 and V3ab (although indirect pathway has been reported to exist between V1 and MT, the other pathway [11, 12]). Ventral pathway is associated with the processing of form, color, complex spatial patterns, contours, and even higher processes like object and face recognition [13]. Dorsal pathway, on he other hand, is characterized by encoding the location of the object, hence it is sometimes referred as 'where' pathway. Depth encoding, and motion sensitivity, which is the topic of this thesis, is heavily coded throughout this dorsal pathway. To put it simply, one could say that ventral pathway is responsible for the perception, while the dorsal pathway is associated with the action of the objects in the world.

1.2 MT+ Region

Motion is highly important for mammalian vision, and ubiquitous in our interaction with the world. Neurons located at what is called the middle temporal area (MT) appears to signal direction of the object, as well as the figure-ground segmentation with majority of the neurons are differentially sensitive to the direction of a moving object [14, 15, 16, 17, 18, 19, 20, 21]. Lesion and micro-stimulation studies show that the disruption of MT+ area results in severe deficits in motion perception [22, 23, 24]. MT neurons are sensitive to movement to many directions, and selective to disparity, therefore, significant changes in the spatial and temporal properties of the moving stimuli influence the activity patterns of MT neurons [3, 25]. Neurons in visual region V3A, which is located on the pathway between V1 and MT, also process depth and motion direction information as do the MT neurons [24]. MT neurons are selectively responsive to the translational movements [26], and receptive fields of MT neurons are generally circular or elliptical in extent and 10 times larger than V1 neurons [27, 28, 21, 29, 8].

There is also dorsal medial superior temporal region (MSTd) that extends anterior to the MT region. Electrophysiological studies on macaque brains show that MSTd neurons receive vestibular signals, and they encode more complex motion patterns (optic flow) such as radial and angular movements, hence they are heavily involved in the perception of self-motion and motion induced by the eye and heading behavior [30, 31, 32]. Neuroimaging and transcraninal magnetic stimulation (TMS) studies show that there is a homolog of MSTd in the human brain, in which functional properties bare strong resemblance to what is observed at macaque MSTd. This region is referred to as MST in human brain [33, 34, 35]. Although MST neurons embody larger receptive field size extending even 10 degree into the ipsilateral visual field [36], and selectively more responsive to the complex motion types compared to MT region, MT and MST are both collectively referred to as MT+ as this network is heavily involved in motion information processing. Therefore, throughout this thesis MT+ denotes the collective cortical region that is compromised of MT and MST.

1.3 Center-Surround Interactions

The visual system receives visual input from the external world that vastly exceeds its processing capacity. Therefore, the system adopts a mechanism for accurately filtering out the uninformative, redundant visual signal to process the informative visual information for the task in hand in the most energy-efficient way possible. One characteristic of the visual coding mechanism is the antagonistic center-surround organization. The spiking activity evoked by the visual stimuli within the neuron's classical receptive field (CRF) is found to be modulated by the sum of the activity evoked by the neighboring visual stimuli [7, 37, 38, 39].

In motion processing, neurons encoding the relative location and depth of the visual information have been reported to embody center-surround receptive field organization. Neurons encoding the stimuli moving towards the preferred direction within the neuron's CRF become inhibited when the an additional stimuli movign to the same preferred direction was added to the surround. First, in their seminal study, Allman and his colleagues show that MT neurons of owl monkeys have this antagonistic center surround organization of receptive field structure [27]. Similar outcome was also observed in macaque MT/V5 [28, 40, 41, 42] Therefore, studies showed that when the CRF of neurons were stimulated with uniform object, they fire relatively less, compared to when they were exposed to spatially dynamic stimuli. Supporting evidence for the role of the surround on the CRF of neurons were followed in subsequent years [43, 44, 45, 25].

The type of the contextual modulation within cortical area MT, which could be either antagonistic (segmentation) or integrative, depending on the type of the stimuli (e.g. dots versus squares), and the ambiguity of the stimuli [46, 47, 48, 46, 25]. When the stimuli elicits ambiguity, MT neurons exhibits neural integration to increase the selectivity of the stimuli, and when the stimuli is unambiguous MT neurons engage in neural segmentation. In correspondence to the observed integrative modulation observed at MT region, there are also wide-field neurons in MT that encode the full field motion pattern (background movement). They

also play critical role in movement caused by eye and the body [43, 41]. Center-surround organization of the receptive field are not only a common mechanism for the visual system, but also ubiquitous in other sensory modalities [49, 50, 51].

Antagonistic center-surround organization of the receptive field of neurons allow the visual system to suppress the uninformative and/or redundant signals (such as the inner areas of the uniform object), and put more weight on more 'interesting' regions, such as the edge of the object, which bears informative signals about the possible interaction of the uniform object with the other objects. Motion correspondence of this outcome was also reported, in which MT neurons fire less to the uniform motion, compared to spatially dynamic motion pattern [52, 53].

Center-surround neurons have been reported to exist at human V1 [54], as well as at cortical area MT+ [17, 46]. In their work, where they single-recorded MT neurons of rhesus monkeys, Bradley and Anderson showed that center-surround interactions of MT neurons also responsible for disparity and the direction of the motion, therefore, play a role in image segmentation [55].

Surround suppression and surround facilitation patterns observed with the method of psychophysics differs when the stimulus properties are manipulated. Contrast level is one property that plays a crucial role in visual motion perception. Studies showed that surround suppression can give away to surround facilitation mechanism if the contrast level of the Gabor grating is low [56, 57, 58, 59]. In other words, contextual modulation at V1 not only depend on the form and the location of the stimulus, but also on the contrast level of the stimuli [59]. The relationship between lowered stimulus strength and lowered suppressive mechanism have also been reported to be in effect when noise is added to the stimuli [60, 46, 47]. Therefore, one can conclude that decreasing the stimulus visibility results in surround facilitation because the visual system has to increase the sensitivity of the incoming visual information by readily integrate them, while increased stimulus strength results in surround suppression to maintain energy-efficient visual coding.

Center-surround interactions were found to be different in the fovea and periphery. Performance for contrast-matching task showed that surround suppression substantially increased as the center-surround stimulus was moved towards periphery, and surround facilitation diminished almost entirely at peripheral locations [61]. It appears peripherally or foveally viewing stimuli trigger linking and grouping activities differentially, thus possibly have different functional roles.

Perceptual correlate of the antagonistic receptive field organization have been reported in the literature. One recent study, investigating performance of motion contrast sensitivity, showed that as the size of the high contrast moving pattern increases, observers require more time to accurately judge the motion direction compared to those with low contrast [1]. In other words, if the grating have low-contrast, increases in size improves performance, whereas if the grating have high contrast, increase in size leads to poorer motion perception performance (see Figure 1.1).

Results obtained from neuroimaging studies indicated a close relationship between aggregated activities of neurons located at MT+ region and the observed behavioral outcome in motion sensitivity discrimination task [1, 2, 62]. When observers were exposed to drifting Gabor grating at differing contrast and size, activities of MT neurons react in a way that shows high correspondence to the behavioral performance. More specifically, MT activity increases when the low-contrast Gabor grating increases in size, parallel to increases in performance in motion discrimination, while increasing the size at high contrast do not result in significant decreases in activity. These findings show that spatial suppression observed with behavioral experiments are associated with neural suppression mechanisms of neurons at cortical area MT (area referred here is equal to MT+).

1.4 Research Question and Hypothesis

The association between MT activity and behavioral performance has led to the assertion that antagonistic center-surround characteristics of MT neurons are responsible for driving the observed behavioral effect. This 'MT-hypothesis' has been supported by findings in literature showing that reduced MT activity is associated with spatial suppression and lower motion sensitivity, whereas increased MT activity is associated with spatial summation and enhanced motion sensitivity [2, 63, 62]. In favor of this hypothesis, disrupting MT+ activity with TMS resulted in decreased spatial suppression in motion discrimination judgments [64]. However, the involvement of earlier visual areas in mediating the behavioral performance have not been systematically analyzed before (but see [62]). One of the major limitation for this was the confluence of V2, V3, and V1, termed as foveal confluence. Borders of V1, V2, and V3 upon foveally viewing the stimuli confluences like multiple rivers confluences and form a delta river upon reaching a sea. This factor makes it harder to investigate the earlier visual areas before the area MT+. To avoid the foveal confluence, we presented the stimuli at the periphery of the observers' visual field.

In the present study, we sought to identify the role of primary visual cortex (V1) in mediating the perceptual consequence of center-surround receptive field organization. Instead of a single sinusoidal grating patch presented centrally, as it was done in previous studies [2, 62], we used a pair of sinusoidal gratings and horizontally displaced them from the central fixation mark. For all participants, we measured duration threshold required for accurately judging whether the two grating patches move at the same direction or not. In the second experiment, we measured BOLD activity at V1 and MT+ while observers peripherally viewed drifting Gabor patches with the same spatial and temporal characteristics used in the first experiment. Influenced by the existing literature, we hypothesized to observe neural summation of motion signals, which would lead to an increase in the activity of MT+ region when the the low-contrasted Gabor patches gets larger. By the same token, we expected to observe reduced neural activity at MT+ (neural suppression) when the high-contrasted Gabor patches increase in

size. For V1 activity, however, due to novelty of this investigation, we held no a-priori hypothesis as to predict the relationship between surround and center for contrast-size interaction in motion perception.

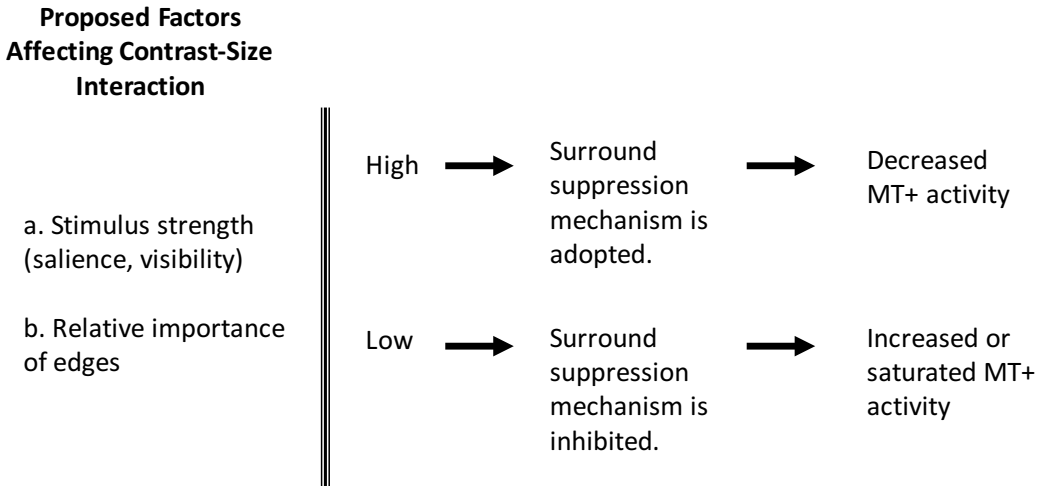


Figure 1.1: **Schematic representation of the relationship between factors affecting the surround suppression and surround facilitation to the activity at visual area MT+.** Proposed factors affecting the contrast size-interaction in motion perception are listed on the left side of the horizontal dashed line, and the influence of each factor are denoted at the right side of it. The intensity of each factor's proposed influence are noted with the words high and low.

Chapter 2

Behavioral Experiment

In this chapter, we present how contrast and size interact in motion perception with a behavioral experiment.

2.1 Materials and Methods

2.1.0.1 Participants

Eleven participants, including myself, participated in the experiment (seven female; age range: 19-28). All participants reported normal or corrected-to-normal vision, and had no history of neurological or visual disorders. Prior to the experimental sessions participants gave their written informed consents. Experimental protocols and procedures were approved by the Human Ethics Committee of Bilkent University.

2.1.0.2 Stimuli, Experimental Procedure, and Analyses

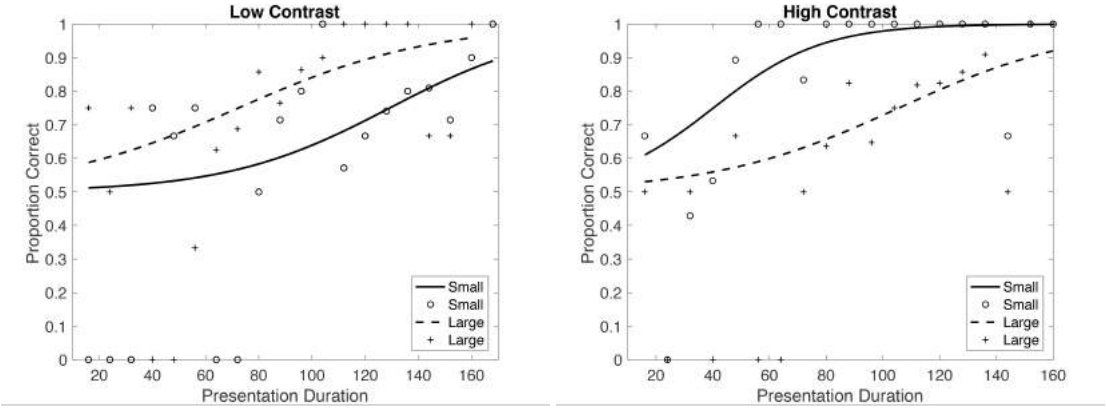
Visual stimuli were presented on a CRT monitor (HP P1230, 22 inch, 1600×1200 resolution, 120 Hz). Participants were seated 75 cm away from the monitor, and their heads were stabilized using a chin rest. Participants' responses were collected via a standard computer keyboard. A gray-scale look-up table, prepared after direct measurements (SpectroCAL, Cambridge Research Systems Ltd., UK), was used to ensure the presentation of correct luminance values. The experimental software was prepared by us using the Java programming platform.

Stimuli were horizontally oriented drifting sine wave gratings (spatial frequency: 1 cycle per degree) weighted by two-dimensional isotropic Gaussian envelopes. Two size- and contrast-matched gratings were simultaneously and briefly presented on a mid-gray background (40.45 cd/m^2) at +/- 9.06 degrees of horizontal eccentricity (the visual angle between the central fixation and the center of the grating). Each grating drifted within the Gaussian envelope (starting phase randomized) at a rate of 4 degree/s either upward or downward. Participants reported whether or not the gratings drifted in the same direction, while maintaining fixation at the central fixation mark. After each trial participants received an auditory feedback (auditory tone of 200 ms duration, 300 Hz for correct and 3800 Hz for incorrect answers). Two size levels (small: 1.67 degrees, large: 8.05 degrees in diameter) and two contrast levels (amplitude of the sine wave grating divided by mean: 2% and 99%) were tested (4 experimental conditions in total). Each condition was blocked in a separate session of 160 trials, and the sessions were randomly ordered for each participant. Before beginning an experimental session, participants completed a short practice session. Based on the performance in the practice session, presentation durations were determined for the starting trials in the experimental session. For the ensuing trials, the experimental program used a two interleaved 3-up 1-down staircase procedure to adaptively adjust the durations. One staircase started from a very short duration, which made the task very hard, the other started from a long duration, on which made the task relatively easier. There were 80 trials in each staircase.

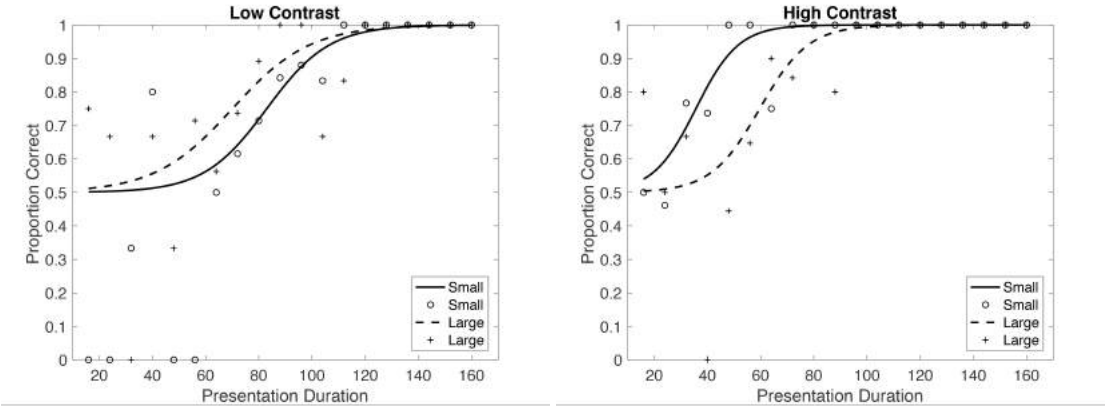
We used the Palamedes toolbox [65] in Octave (http://www.octave.org) to fit psychometric functions (logistic function) to the data for each observer and condition, and to estimate duration thresholds (79% success rate) and standard errors (see Figure 2.1). We calculated standard errors of the estimated thresholds with bootstrapping procedure. Analysis of variances (ANOVA) with two factors (size and contrast) was performed to compare the thresholds at group level using SPSS Version 19 (SPSS Inc., Chicago, IL). Additionally, discrimination thresholds of small and large stimuli were compared using two-tailed paired-samples Student's t-test both for low-contrast and high-contrast stimuli.

2.2 Results

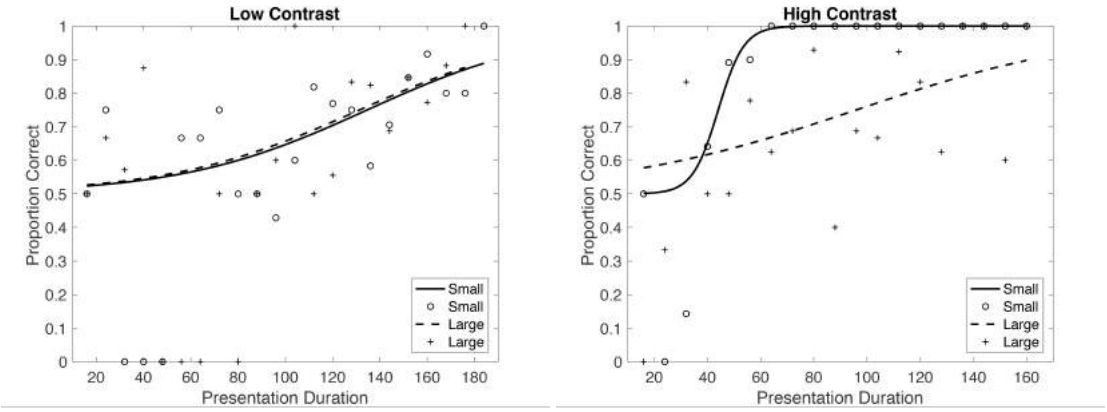
In this experiment, we measured duration threshold for accurately judging the drift direction of Gabor patches at two size (1.67 and 8.05 degrees) and contrast levels (2% and 99%). We calculated the overall threshold for all participants by averaging individual threshold value of each participant for each condition. Results are shown in Figure 2.2. Analyses showed that main effect of contrast ($F(1,10) = 15.84$, $p < 0.01$) was statistically significant and main effect of size ($F(1,10) = 4.86$, $p = 0.052$) was close to significance. Also, the interaction between contrast and size was statistically significant ($F(1,10) = 39.72$, $p < 0.001$). Two-tailed paired-samples Student's t-tests showed that for low-contrast stimuli, discrimination threshold decreases as size gets bigger (for small stimuli: M = 107.23, SEM = 6.22; for large stimuli: M = 81.327, SEM = 6.21; $t(10) = 5.96$; $p < 0.001$). On the contrary, for high-contrast stimuli, discrimination threshold increases as size gets bigger (for small stimuli: M = 39.83, SEM = 2.24; for large stimuli: M = 98.28, SEM = 11.85; $t(10) = -4.41$; $p < 0.01$). These results clearly replicate the size–contrast interaction in motion perception even when stimuli is presented at the periphery.



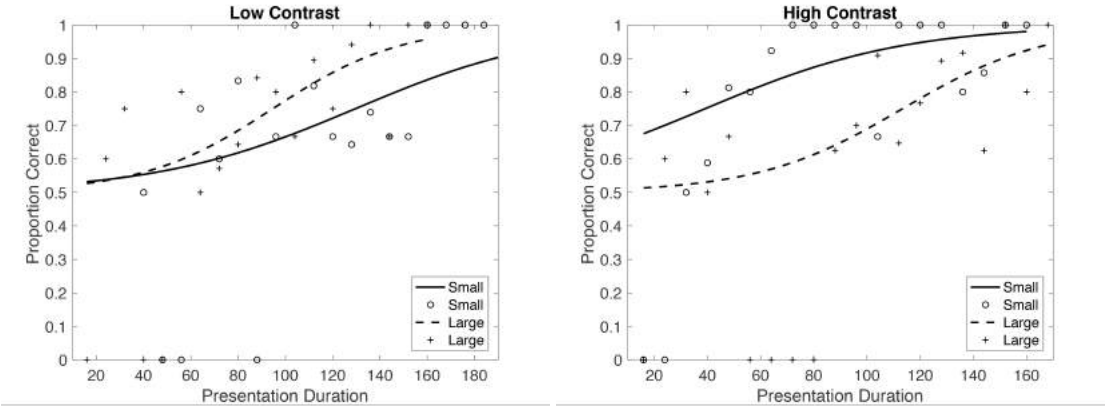
(a) **Participant 1** Duration threshold for low contrast small stimuli: 129.22 ms (SE: 12.11), for low contrast large stimuli: 79.34 (SE: 6.60), for high contrast small stimuli: 43.89 (SE: 2.58), for high contrast large stimuli: 102.56 (SE: 8.36).



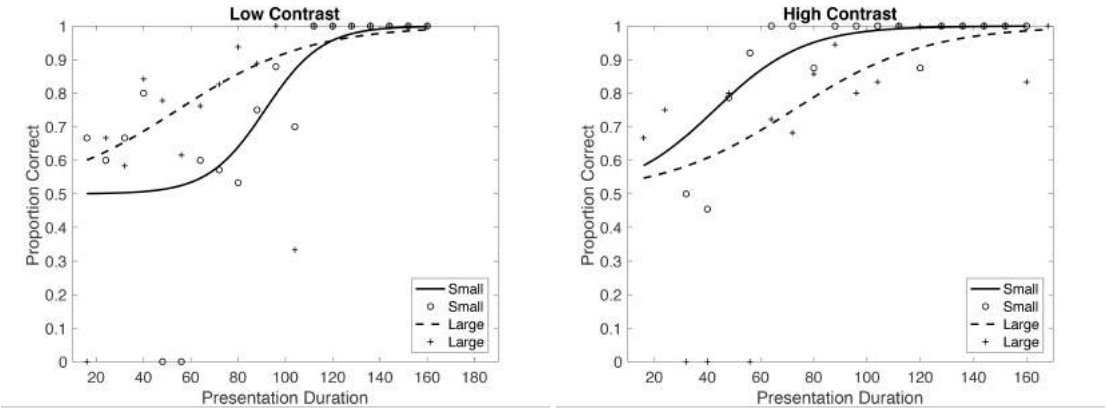
(b) **Participant 2** Duration threshold for low contrast small stimuli: 82.95 ms (SE: 5.52), for low contrast large stimuli: 70.04 (SE: 7.10), for high contrast small stimuli: 35.64 (SE: 3.70), for high contrast large stimuli: 59.65 (SE: 4.32).



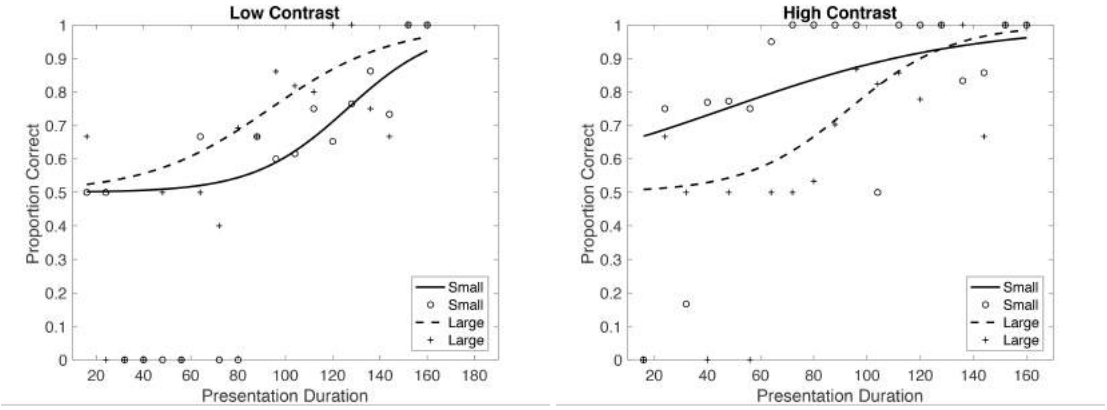
(c) **Participant 3** Duration threshold for low contrast small stimuli: 134.58 ms (SE: 12.83), for low contrast large stimuli: 131.34 (SE: 16.25), for high contrast small stimuli: 44.05 (SE: 2.36), for high contrast large stimuli: 95.93 (SE: 20.29).



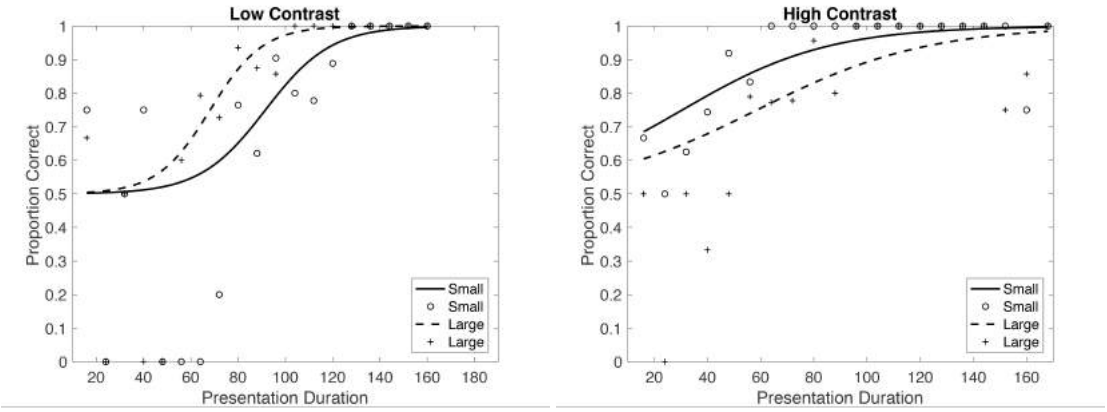
(d) **Participant 4** Duration threshold for low contrast small stimuli: 129.63 ms (SE: 15.23), for low contrast large stimuli: 94.00 (SE: 10.18), for high contrast small stimuli: 48.00 (SE: 4.90), for high contrast large stimuli: 114.23 (SE: 11.81).



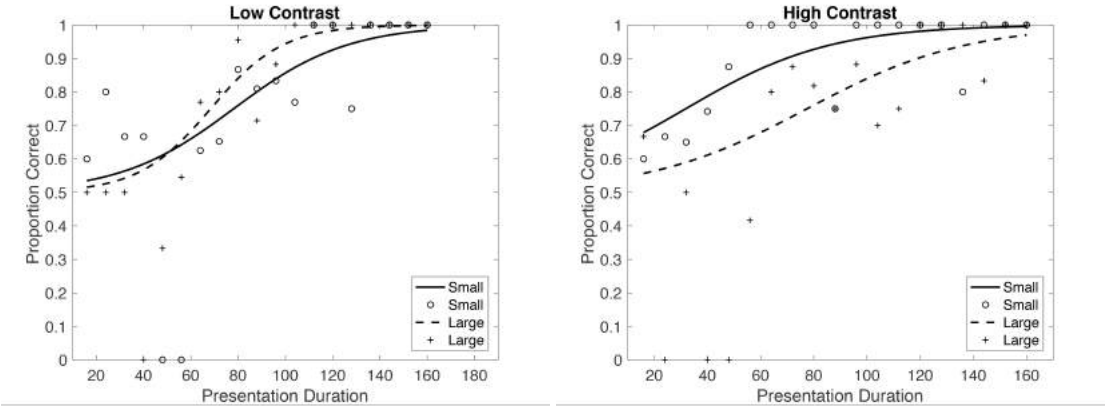
(e) **Participant 5** Duration threshold for low contrast small stimuli: 91.41 ms (SE: 5.36), for low contrast large stimuli: 54.39 (SE: 11..94), for high contrast small stimuli: 46.76 (SE: 5.13), for high contrast large stimuli: 74.32 (SE: 6.50).



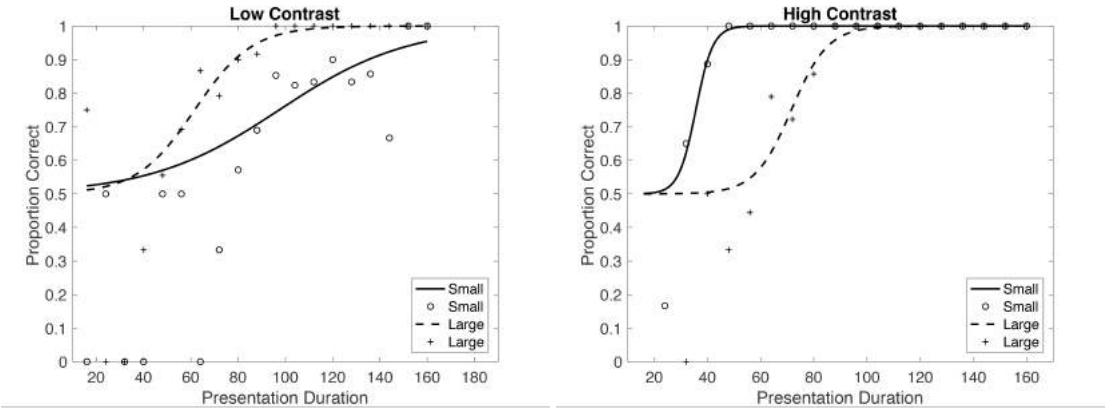
(f) **Participant 6** Duration threshold for low contrast small stimuli: 126.18 ms (SE: 13.10), for low contrast large stimuli: 92.74 (SE: 5.03), for high contrast small stimuli: 47.01 (SE: 25.22), for high contrast large stimuli: 93.15 (SE: 7.21).



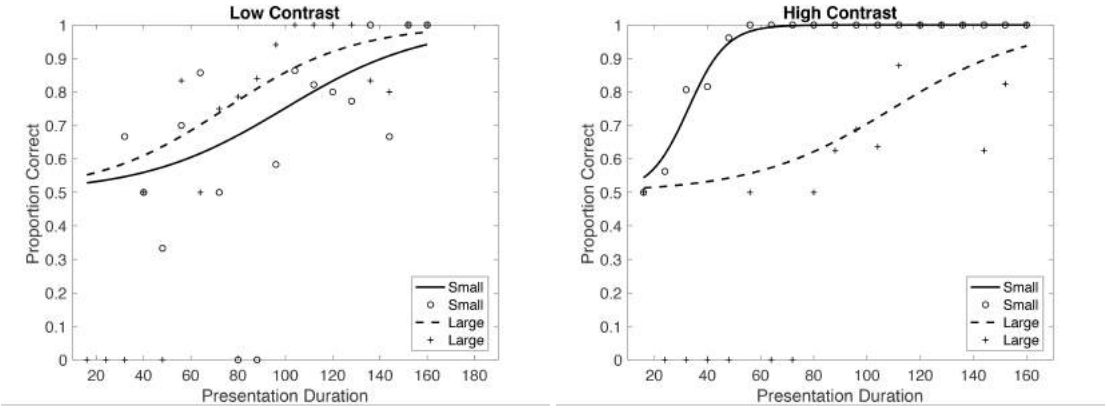
(g) **Participant 7** Duration threshold for low contrast small stimuli: 91.54 ms (SE: 6.05), for low contrast large stimuli: 65.15 (SE: 4.55), for high contrast small stimuli: 39.44 (SE: 4.27), for high contrast large stimuli: 63.48 (SE: 5.33).



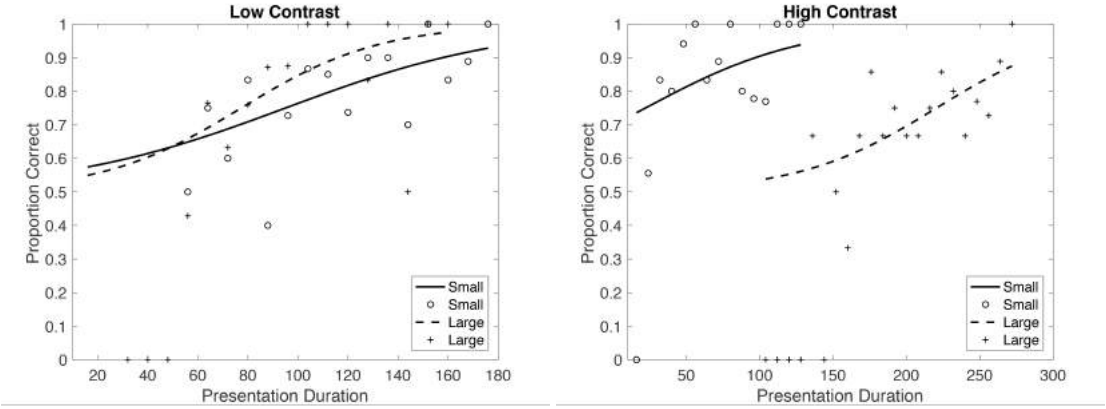
(h) **Participant 8** Duration threshold for low contrast small stimuli: 78.13 ms (SE: 9.53), for low contrast large stimuli: 68.40 (SE: 6.61), for high contrast small stimuli: 36.48 (SE: 6.63), for high contrast large stimuli: 77.49 (SE: 14.74).



(i) **Participant 9** Duration threshold for low contrast small stimuli: 113.12 ms (SE: 6.63), for low contrast large stimuli: 68.82 (SE: 4.42), for high contrast small stimuli: 37.77 (SE: 1.52), for high contrast large stimuli: 75.88 (SE: 2.21).



(j) **Participant 10** Duration threshold for low contrast small stimuli: 115.38 ms (SE: 7.41), for low contrast large stimuli: 89.27 (SE: 9.93), for high contrast small stimuli: 36.94 (SE: 2.80), for high contrast large stimuli: 124.80 (SE: 10.63).



(k) **Participant 11** Duration threshold for low contrast small stimuli: 95.1 ms (SE: 1.85), for low contrast large stimuli: 75.8 (SE: 0.92), for high contrast small stimuli: 22.2 (SE: 2.14), for high contrast large stimuli: 96.18 (SE: 5.25).

Figure 2.1: **Psychometric function fit plotted separately for each participant.** Proportion of correct responses were plotted as a function of presentation duration (ms).

2.3 Discussion

In this experiment, we asked whether motion contrast sensitivity performance is in line with the findings in the existing literature, when the stimuli are horizontally displaced at the periphery. Results revealed that observers' performance for accurately judging the drift direction of the peripherally presented Gabor patches improved with size, if the stimuli have low contrast, but deteriorated if the stimuli have high contrast. Therefore, results were in line with the findings in the literature [1, 2, 62].

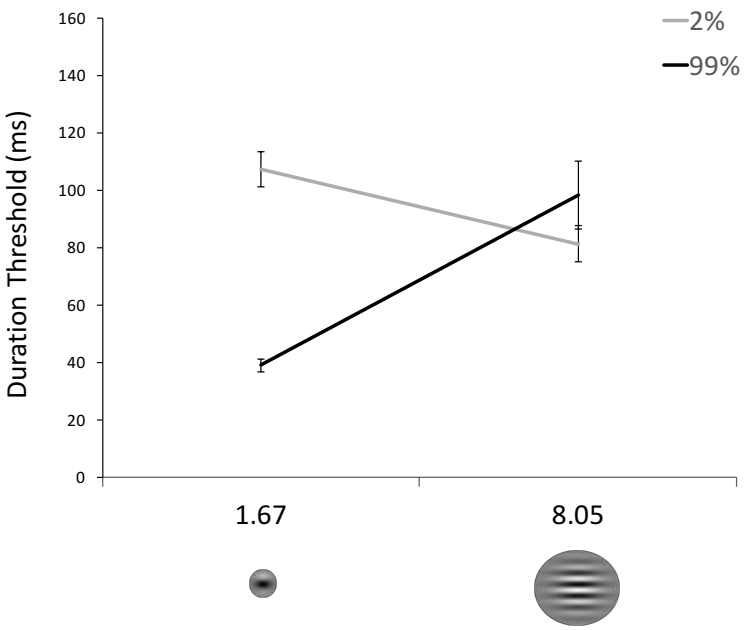


Figure 2.2: **Mean values of duration thresholds for eleven participants under four conditions**. For low-contrast stimuli, discrimination threshold decreases as size gets bigger. On the contrary, for high-contrast stimuli, discrimination threshold increases as size gets bigger. These results clearly replicate the size – contrast interaction in motion perception even when stimuli is presented at the periphery. Error bars represent SEM.

Chapter 3

Functional MRI Experiment

In this chapter we studied the neuronal correlates of the behavioral effect using the blood-oxygen-level dependent (BOLD) fMRI responses as an index for the investigation of neural mechanism involved at the primary visual cortex (V1) and middle temporal complex (MT+). We recorded the BOLD responses in MT+ and V1 in response to the Gabor grating patches with same spatial and temporal paradigm used in the first experiment. We aimed to investigate the role of surrounding region to the neural activity patterns measured at the center, which is operationally defined as the cortical area that is selectively responsive to the small size moving grating. To measure the quantity of change the surround causes at the neural activity patterns, we subtracted the BOLD activity evoked by the large grating from the activity evoked by the small grating for both contrast levels at V1 and MT+ ROIs, resulting area was referred as the sub-ROI. Considering sub-ROI was stimulated at both conditions, the differences in activity patterns between large and small visual stimuli have been interpreted as the influence of surrounding region.

Presenting the Gabor patches at the periphery allowed us to avoid foveal confluence, therefore, allowed us to investigate the V1 region in isolation. We show that spatial suppression and spatial facilitation of motion signals observed with

the behavioral experiment were associated with the neural mechanism of center-surround neurons located at the cortical area MT+, not at primary visual cortex, V1.

3.0.0.1 Participants

Six volunteers (age range: 23-26; mean age: 25; three male) participated in the experiment. Three of the volunteers participated also in the first experiment. All participants had normal or corrected-to-normal vision, and had no history of neurological or visual disorders. Participants gave their written informed consents prior to each fMRI session. Experimental protocols and procedures were approved by Bilkent University Human Ethics Committee.

3.0.0.2 Data Acquisition & Experimental Setup

MR images were collected on a 3 Tesla Siemens Trio MR scanner (Magnetom Trio, Siemens AG, Erlangen, Germany) with a 32-channel array head coil in the National Magnetic Resonance Research Center (UMRAM), Bilkent University. Each MR session started with a structural run followed by two localizer and four experimental functional runs, totaling approximately 1 hour in duration. Structural data were acquired using a T1-weighted 3-D anatomical scan (TR: 2600 ms, spatial resolution: 1 mm^3 isotropic, number of slices: 176). Functional images were acquired with a T2*-weighted gradient-recalled echo-planar imaging (EPI) sequence (TR: 2000 ms, TE: 35 ms, spatial resolution: 3x3x3 mm^3, number of slices: 30, slice orientation: parallel to calcarine sulcus). Visual stimuli were presented on an MR-safe LCD Monitor (TELEMED PMEco, Istanbul, 32 inch, 1920 X 1080 resolution, vertical refresh: 60 Hz). The monitor was placed near the rear end of the scanner bore, and viewed by the participants from a distance of 165 cm via a mirror mounted on the head coil. The stimuli were generated and presented using Python and the Psychopy package [66].

3.0.0.3 Visual Stimuli & Experimental Design

Visual stimuli were drifting Gabor patches as in the behavioral experiment. Two size (small: 1.67 degree, large: 8.05 degree) and two contrast levels (2% and 99%) were tested. Due to the limits of the visual display system, gratings were presented at +/- 8.02 degrees of horizontal eccentricity (not 9.06 degrees as in the behavioral experiment), and drifted with a rate of 6 degree/second either upward or downward for the duration of 2 seconds. Both Gabor patches drift in the same direction simultaneously, and alternate direction at every two seconds to avoid motion adaptation.

A functional run was composed of 12-second 'active' and 12-second 'blank' blocks. In the active blocks drifting Gabor patches were presented, and in the blank blocks only the fixation mark remained visible on the screen (see Figure 3.1). In alternating active blocks small and large drifting Gabor patches were shown, each for 6 times. Contrast level was kept constant in a run. Two experimental runs were conducted for each contrast level in a session. The runs started with an initial blank period of 24 seconds to allow hemodynamic response reach a steady state. Total duration of a functional run was around 5 minutes. Figure 3.1 shows the schematic representation of a experimental scan.

Both to ensure fixation, and to control for spatial attention, throughout an entire functional run, participants performed a demanding fixation task. The color of the fixation mark (0.3 degree solid square) changed randomly from its original color (gray) to either red or yellow for a duration of 50 ms at a randomly designated interval between 250 to 1500 ms. Participants' task was to report the changes in color of the fixation mark by pressing the designated button on an MR-safe response button-box (Fiber Optic Response Devices Package 904, Current Designs).

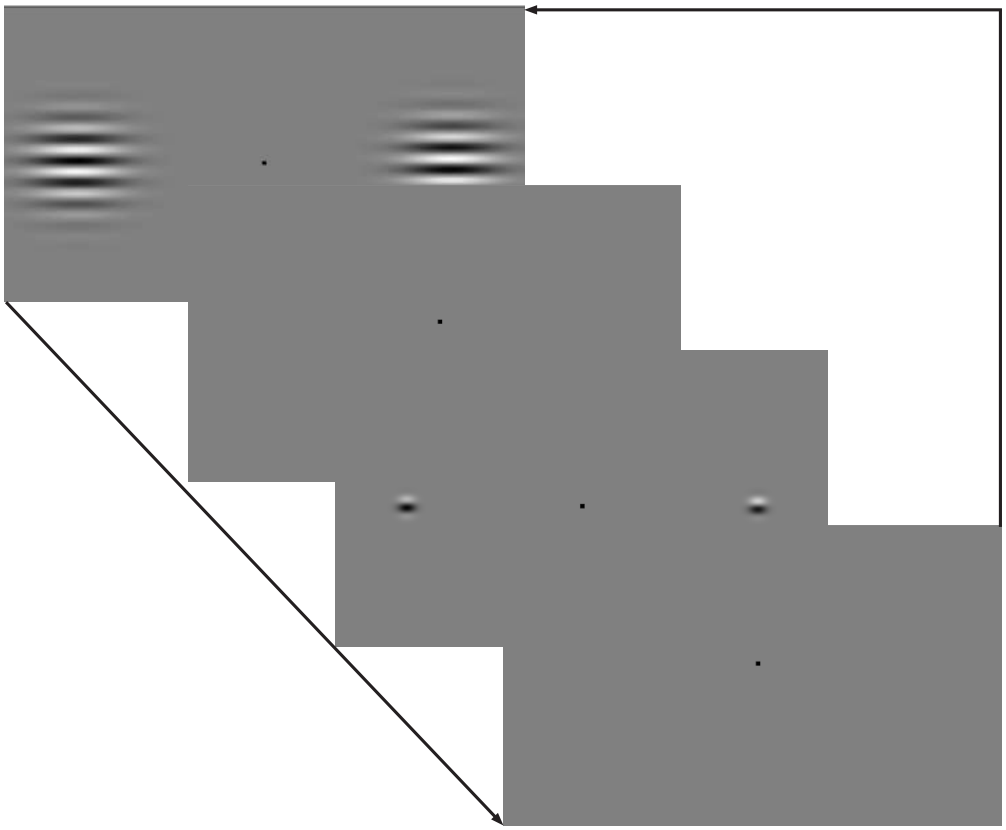


Figure 3.1: **Schematic representation of the visual paradigm of a single cycle of a experimantal scan in the fMRI experiment**. Participants viewed drifting Gabor patches during a 12-second active block followed by a 12-second blank block. Large (8.05 degree) and small (1.67 degree) Gabor patches were presented in alternating active blocks. This cycle was repeated for six times within a single run. Contrast was kept constant in a run (either 2% or 99%), and there were 4 experimental conditions in total (two with 2% and two for 99% contrast levels).

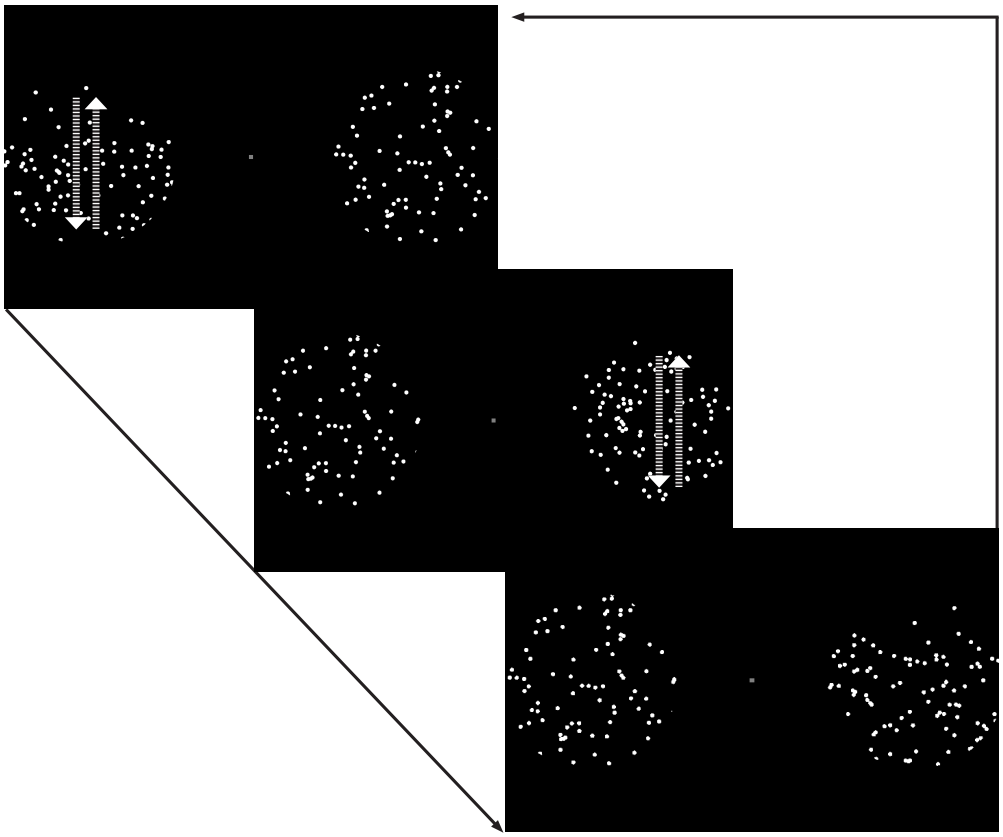


Figure 3.2: **Schematic representation of the design used for the MT+ localizer scan**. In each 12-seconds long blocks, participants viewed circular shaped field of dots that were horizontally displaced from both sides of the fixation square. Red dashed arrows indicate the dot field in motion, and absence of it indicate that dots in that field remain stationary. In the actual experiment no arrows were used. This cycle was repeated for eight times within a single run. See main text for details.

3.0.0.4 Localization of Region of Interest in MT+

The region of interest (ROI) in MT+ was localized in two steps. In the first step, we localized the MT+ complex using the established methods in literature [20, 67, 31]. In the second step, we identified the ROI within MT+ that hosts neurons that are responsive to the small sized stimuli (same stimuli used in the experimental scans). Details are described in the following paragraphs.

MT+ complex localization. We localized the MT+ complex using fields of dynamic and static dots. The dot fields were comprised of 100 dots on a black background within a 8 degree diameter circular aperture. The center of the fields were 8.02 degrees to the left and to the right of the fixation point. BOLD responses were collected for three types of configurations, each presented for 12-seconds: right field dynamic (left static), left field dynamic (right static), and static (both fields). Figure 3.2 show the schematic representation of the visual setup used for MT+ localizer. This cycle of presentation was repeated eight times in a run. The dynamic blocks included four motion types that were presented in pseudo-random and counter-balanced order. They were radial, angular, and translational along the horizontal axis and translational movement along the vertical axes. The motion speed was 6 degree/second. The duration for each type of motion was 2 seconds, and the direction of motion was reversed after every two seconds to minimize adaptation.

Using General Linear Model (GLM) we localized MT+ in each hemisphere by identifying the voxels that respond strongly to dynamic contralateral fields compared to static fields (see Figure 3.3). The visual paradigm we used in the motion localizer (see Figure 3.2) allow us to identify MST using the MST's large receptive field characteristics. Therefore, contrasting voxels that were differentially active for ipsilaterally viewed stimuli from voxels that are responsive to the stationary visual field revealed the MST region. As for the MT region, we identified it by contrasting activity evoked by the ipsilaterally stimulated region (MST) from the activity evoked by the contralaterally viewed stimuli.

ROI within MT+. Next we localized the ROI within the MT+ with an independent localizer run using drifting gratings. The size and position of the gratings were the same as the small gratings used in the experimental runs, but their contrast was different (60%). Our aim in this study is to measure the contextual influence of the surrounding region to the central region, therefore, we sought to compare the responses from the neuronal populations that are responsive to the region of the visual field that overlaps with the small sized grating, so that the corresponding activity difference evoked by presenting the large sized stimuli could either suppress or facilitate activity at the center. With this aim, we applied methods of GLM on the masked region (MT+), and identified voxels that are selectively responsive to the corresponding small size grating. All subsequent analyses were performed from the data extracted from this ROI.

3.0.0.5 Localization of ROI in V1

We identified the V1 ROI based on anatomical landmarks and an independent localizer analysis. Stimuli were drifting Gabor patterns presented with same size and location as the small Gabor of experimental runs, but had different contrast (60%). Cortical regions responding differentially more strongly to the drifting pattern and located anteriorly in the calcarine sulcus were identified as the V1 ROI (see Figure 3.4). All subsequent analyses were performed on the experimental data extracted from this ROI.

3.0.0.6 Analyses

Anatomical and functional data were preprocessed and analyzed using the BrainVoyager QX software (Brain Innovation, The Netherlands). Preprocessing steps for the functional images included head motion correction, high-pass temporal filtering and slice scan time correction. T1-weighted structural images were transformed into AC-PC plane, and aligned with the functional images. For each brain the border between white matter and cortex was drawn, and an inflated three-dimensional model of the cortex was generated. Functional maps were projected

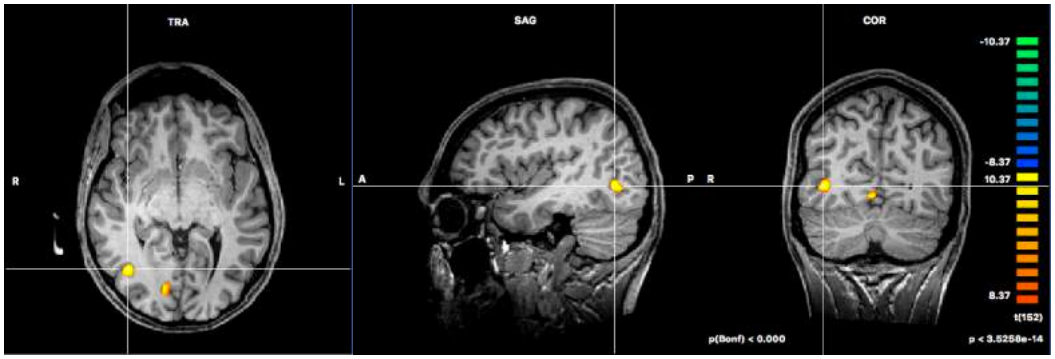


Figure 3.3: **Representative images of MT+ on a T1-weighted structural scan.** Images are taken from transverse, sagittal and coronal plane (left to right) and intersection of two white colored lines show MT+ ROI located at the participant's left hemisphere. Region show the area comprised of voxels that were responsive to the motion. Results were obtained by contrasting the activity evoked by contralateral visual field from activity evoked by the static field. Note that sub-ROI were extracted from the region showed above. See main text for details. Threshold information were color coded, and color scheme depicted at the right side.

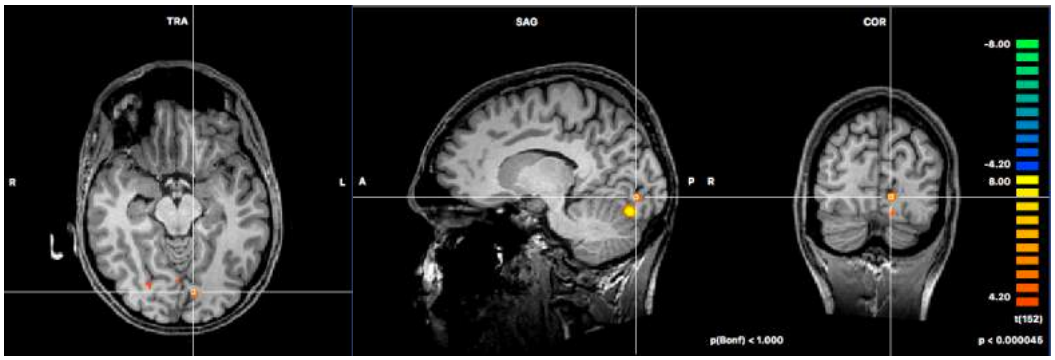


Figure 3.4: **Representative images of V1 ROI mapped onto T1-weighted structural image of a participant's right hemisphere.** The area highlighted with two intersecting line show the region that were significantly responsive to the small-sized Gabor grating. Results were obtained by contrasting the activity evoked by small-sized stimuli and the blank visual stimulation (see main text for details). Images were taken from transverse, sagittal and coronal plane (left to right). Threshold information were color coded, and at the color scheme depicted at the right side.

onto the inflated cortex to aid visualization of subsequent analyses.

Followed by identifying the sub-ROI as described above, the time courses of BOLD responses within the ROIs were extracted for further analyses with a custom-written python code. First, pre-period event related averages were computed for each condition using the average of the two volumes prior to the onset of the active blocks as the baseline. Percent BOLD changes were calculated based on the baseline of each conditions within a run. Next, average of the 4th to 6th volumes of this event-related time course was calculated. This average was used as the mean response for that condition in further analyses (see Figure 3.5 and Figure 3.6).

To quantify the changes in fMRI response evoked by increasing stimulus size, we calculated a size index (SI) defined as $SI = B_L - B_S$, where B_L is the mean response to large grating, B_S is the mean response to small grating. A positive SI means increased response with increasing size (spatial summation), a negative

SI means decreased response with increasing size (spatial suppression).

3.1 Results

3.1.1 MT+

Figure 3.7 shows averaged fMRI response magnitudes for MT+ region in response to changes in contrast and size of the stimuli. To investigate the effect of contrast and size to the changes in BOLD response, we applied A 2 × 2 repeated-measures ANOVA for the contrast level (% 2 and % 99) and size (1.67 and 9.05 degree) as factors. Results revealed a main effect of contrast on the activity of MT+ ($F(1,5) = 25.06$, $p < 0.01$). However, no main effect of size on the fMRI response ($F(1,5) = 2.11$, $p = 0.21$), nor an interaction involving size and contrast was found ($F(1,5) = 4.34$, $p = 0.09$).

Influenced by the existing literature [2, 62], we hypothesized to observe greater activity with size at low contrast compared to activity changes with size at high contrast. Therefore, we applied two-tailed t-test to investigate the changes in fMRI response magnitude for differing contrast and size levels. Figure 3.7 shows the resulting fMRI response patterns evoked by small and large sized stimuli. At low contrast, increasing the size of the stimuli resulted in greater MT+ activity (for small stimuli: M = -0.13, SEM = 0.17; for large stimuli: M = 0.49, SEM = 0.18). However, two-tailed paired samples t-test revealed that the difference was not significant ($F(1,5) = 1.90$, $p = 0.12$). At high contrast, results show that MT+ activity did not vary significantly with size, as the difference between MT+ activity evoked by small and large sized stimuli were not significant (for small stimuli: M = 0.99, SEM = 0.12; for large stimuli: M = 0.81, SEM = 0.13; $F(1,5) = 1.53$, $p = 0.18$). For small stimuli, we found that MT+ activity increased significantly with increased contrast (for small low-contrasted stimuli: M = -0.13, SEM = 0.17; for small high-contrasted stimuli: M = 0.99, SEM = 0.12; $F(1,5) = 4.21$, p = 0.008). See Figure 3.5 for timecourse data of MT+ region.

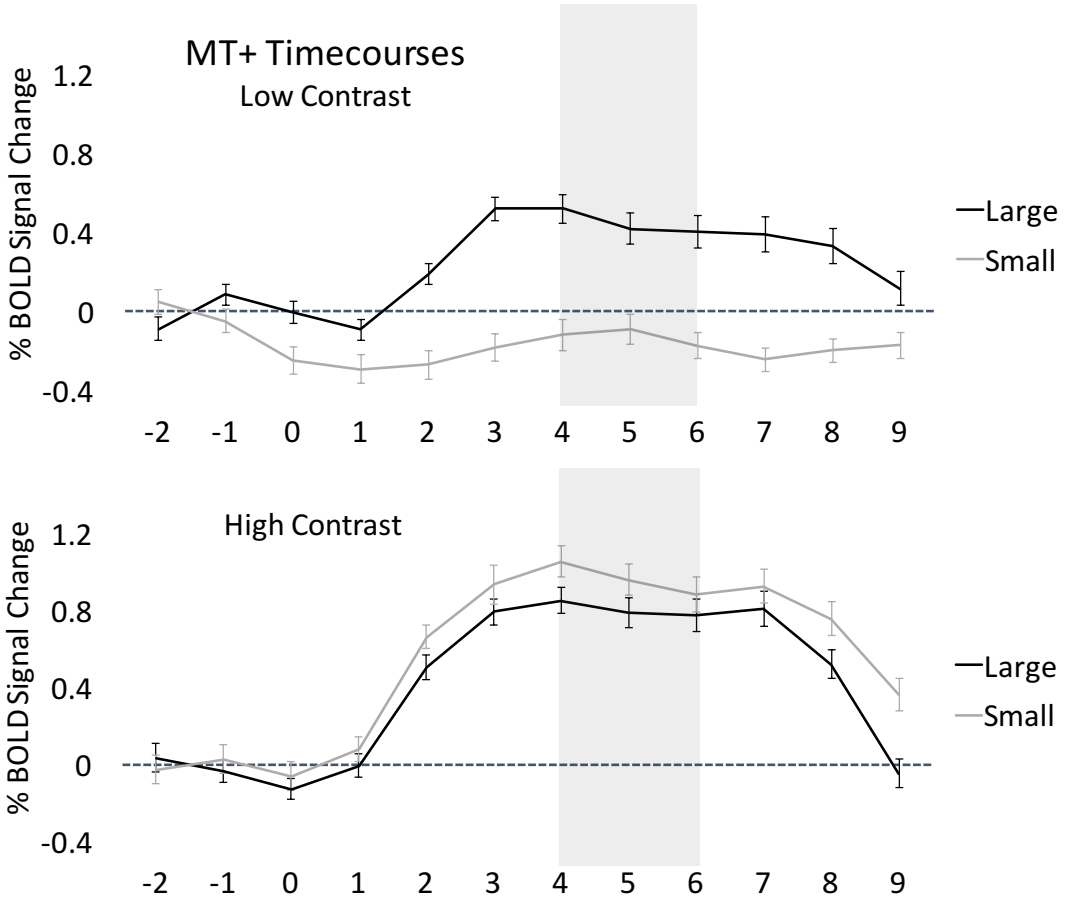


Figure 3.5: **Timecourse data of sub-ROI MT+ plotted as a fMRI response evoked by large (black) and small (gray) stimuli.** Upper graph represents the data obtained when the stimuli had low contrast and the bottom graph represents the data obtained when the stimuli had high contrast. Dark gray rectangle region denotes the time window where the peak response was calculated. On the x-axis, 0 denotes the onset time, and minus values indicate the time window where previous block was shown, which was blank stimulation. Per-condition normalization have been applied. Error bars represent Mean +- SEM.

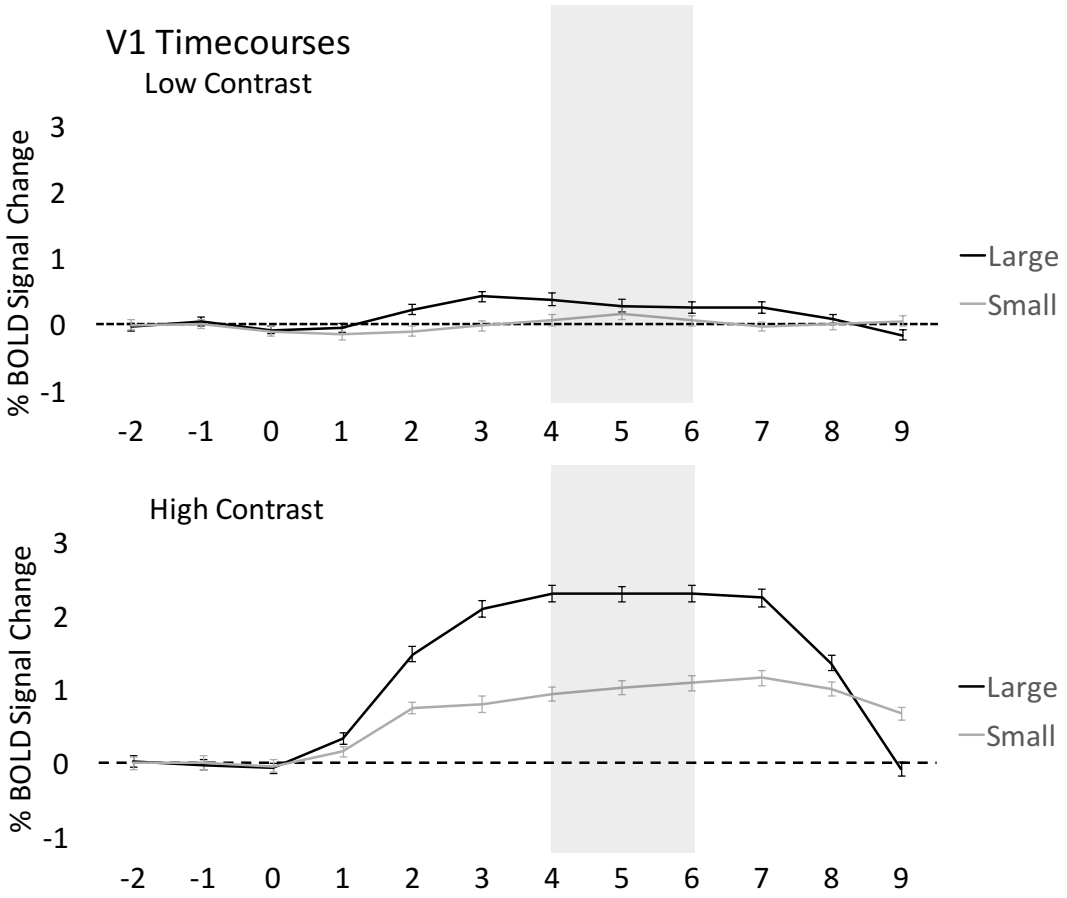


Figure 3.6: **Timecourse data of sub-ROI V1 plotted as a fMRI response evoked by large (black) and small (gray) stimuli**. X-axis denote the TR values (each lasting two seconds).Dark gray rectangle region denotes the time window where the peak response was calculated. Value 0 at the y-axis denotes the onset time, and minus values indicate the blank stimulation time before onset of the stimuli. Error bars represent Mean +- SEM.

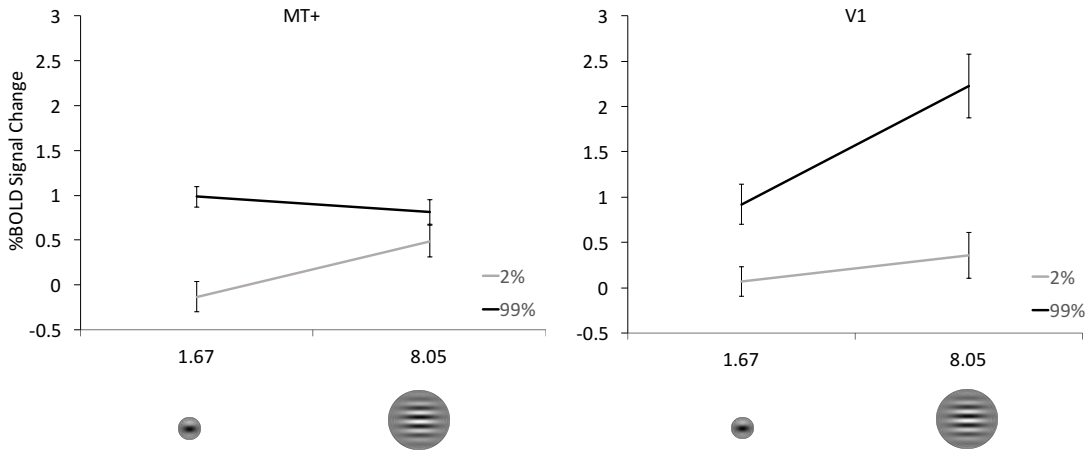


Figure 3.7: **fMRI response magnitude for MT+ and V1 regions.** Plot of percent signal change averaged for all individuals in response to two-way interaction of contrast and size in MT+ **(left)** and V1 **(right)**. Error bars represent SEM.

After calculation of SI as described above, we performed paired sample t-test to investigate the effect of size in changing the MT+ activity. Figure 3.8 shows individual SI values for all participants and the mean SI for all. Results revealed a positive SI value at low contrast, meaning MT+ activity increased with size at low contrast (neural summation) (M_{SI}= 0.617, SEM = 0.325). However, one sample t-test revealed that the positive SI value was not significantly greater than zero (t(5) = 1.90, $p = 0.058$). At high contrast, SI resulted in negative value, which shows that increasing the size of the stimuli at high contrast resulted in decreased MT+ activity (neural suppression) (M_{SI}= -0.173, SEM = 0.113). However, one-sample t-test revealed that the negative SI value was not significantly less than zero (t(5) = -1.53, $p = 0.093$). All things considered, results showed the amount of effect of size to the MT+ activity was greater if the stimuli had low contrast, compared to high contrast.

3.1.2 V1 Results

To investigate the role of contrast and size on the V1 activity, we applied two-way repeated measures ANOVA with the contrast (low and high) and size (small and large) as factors. Two-way repeated measures ANOVA revealed a main effect of contrast, which showed that the contrast level of the stimuli significantly affected the V1 activity ($F(1,5) = 15.23$, $p = 0.011$). ANOVA also revealed a main effect of size ($F(1,5) = 26.530$, $p = 0.004$), as well as an interaction affecting the V1 activity ($F(1,5) = 7.31$, $p = 0.043$).

We applied two-tailed t-test to investigate the role of size and contrast level in mediating V1 activity. Figure 3.7 shows the averaged fMRI response magnitudes for V1 region in response to contrast and size factors. Two-tailed t-test revealed that V1 activity did not change significantly with size at low contrast (for small stimuli: M = 0.07, SEM = 0.16; for large stimuli: M = 0.36, SEM = 0.25; $t(5) = 1.04$; $p = 0.347$). In other words, response magnitude evoked by both stimuli sizes at low contrast were not significantly different from each other. On the other hand, t-test showed that V1 activity increased significantly with size for high contrast (for small stimuli: M = 0.92, SEM = 0.22; for large stimuli: M = 2.23, SEM = 0.35; $t(5) = 6.52$; $p = 0.001$). See Figure 3.6 for timecourse data V1 region.

To further investigate the effect of size to V1 activity, we applied two-tailed t-test on the data indexed with size (SI). Figure 3.8 shows SI values for individual participants and mean value for all. At low contrast, SI had a positive value which indicated that V1 activity increased with stimuli size (neural summation) (M_{SI}= 0.291, SEM = 0.280). However, one-tailed t-test revealed that it was not significantly greater than zero ($t(5) = 1.04$; $p = 0.173$). At high contrast, SI value was positive as well (M_{SI}= 1.306, SEM = 0.200), and one-tail t-test revealed that it was significantly greater than zero ($t(5) = 6.53$; $p < 0.001$). We did not hold an a-priori hypothesis regarding the role of contrast in mediating the changes at V1 activity with increasing stimuli size, therefore, we tested whether SI values for both contrast levels were significantly different from each other. Two-tailed

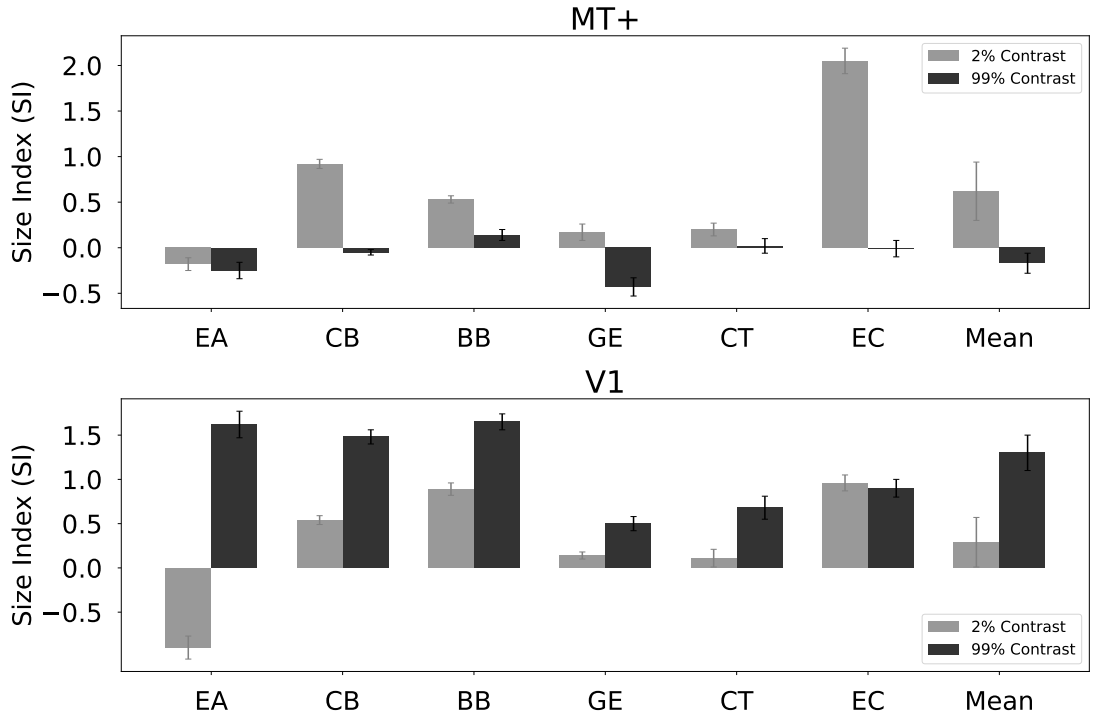


Figure 3.8: **Bar graph representing the effect of size to the percent BOLD response, displayed separately for all participants.** Negative Size Index (SI) values indicate that increasing the size of the stimuli resulted in decreased BOLD signal activity (spatial suppression), whereas positive SI values indicated that increasing the size of the stimuli resulted in increased BOLD signal activity (spatial summation). Right-most bar represent the average SI value for all participants. Error bars represent SEM.

t-test revealed that SI values for low and high contrast were indeed significantly different from each other ($F(1,5)$ = -2.70, $p = 0.042$). Furthermore, To decide on the direction of the difference, we performed one-tailed t-test, and results showed that SI value for high contrast was greater than SI value for low contrast ($F(1,5)$ = 2.70, p = 0.021). This result showed that increasing the size of the grating at high contrast caused significantly greater activity at the groups of neurons located at the sub-ROI in V1, compared to activity evoked by increased size at low contrast. All in all, results showed that V1 activity increased significantly with size at high contrast, but remained unchanged with size at low contrast, and the size effect was greater in magnitude when contrast was high.

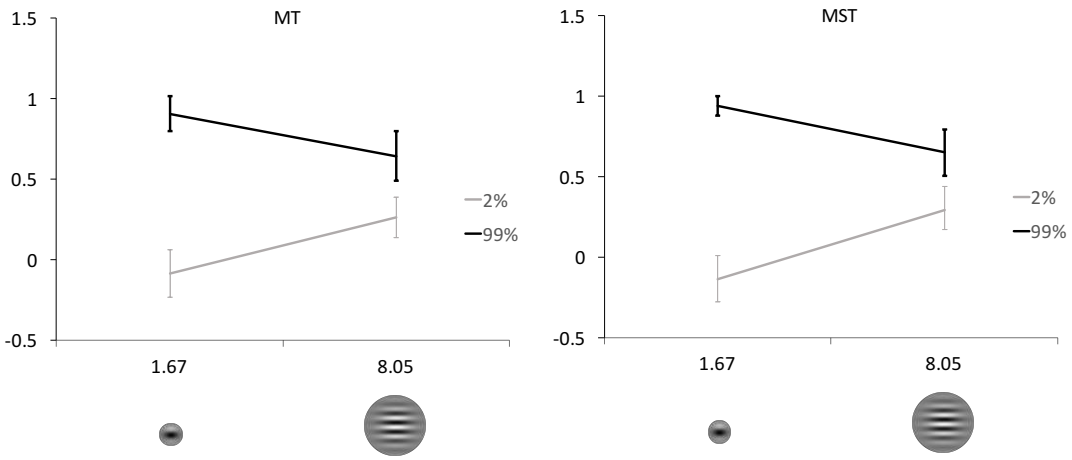


Figure 3.9: **Plot of averaged fMRI response in MT and MST regions.** Error bars represent Mean +- SEM.

3.1.3 Other Regions

3.1.3.1 MT & MST

We identified MT and MST regions with the help of their receptive field characteristics. Figure 3.9 shows the averaged fMRI BOLD activity for MT and MST regions. The trends were very similar to MT+ region. We applied A 2 $\times$ 2 repeated-measures ANOVA for the contrast level (% 2 and % 99) and size (1.67 and 9.05 degree) as factors for the two regions. At MT, two-way repeated measures ANOVA revealed a main effect of contrast (F(1,5) = 19.48, p = 0.007). However, no main of size (F(1,5) = 0.128, p = 0.735), nor an interaction were found (F(1,5) = 5.498, p = 0.066). Paired-samples t-test results showed that MT activity remained the same with size at low contrast (for small stimuli: M = -0.08, SEM = 0.15; for large stimuli: M = 0.26, SEM = 0.12; F(1,5) = 1.50, p = 0.19). At high contrast, however, activity significantly lowered with size (for small stimuli: M = 0.91, SEM = 0.11; for large stimuli: M = 0.64, SEM = 0.16; F(1,5) = 2.84, p = 0.036). At MST, two-way repeated measures ANOVA revealed a main effect of contrast (F(1,5) = 28.215, p = 0.003). However, the results revealed no main effect of size on BOLD activity (F(1,5) = 0.324, p = 0.594). As for the

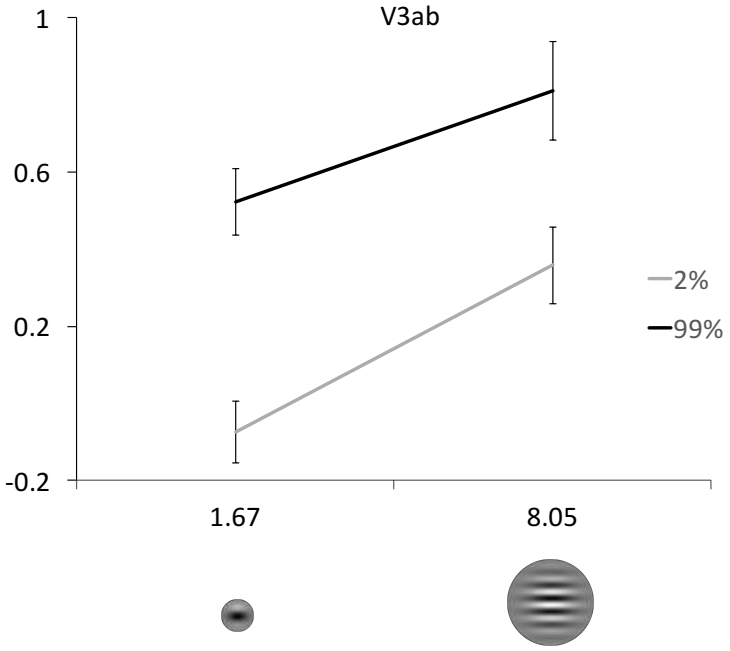


Figure 3.10: **Plot of averaged fMRI BOLD activity at V3ab region in response to contrast and size levels**. Error bars represent SEM.

interaction involving size and contrast levels, ANOVA revealed close to significant results (F(1,5) = 6.519, $p = 0.051$). Results obtained from paired-samples t-test showed that MST activity were not significantly different at different sizes for low contrast (for small stimuli: M = -0.13, SEM = 0.14; for large stimuli: M = 0.29, SEM = 0.14;$F(1,5) = 1.80$, 0.120), nor for high contrast (for small stimuli: M = 0.94, SEM = 0.06; for large stimuli: M = 0.65, SEM = 0.14; $F(1,5) = 2.32$, p = 0.068).

3.1.3.2 V3ab

We identified the visual area V3ab by using the anatomical cues as landmarks. Figure 3.10 shows the averaged BOLD activity of V3ab region in response to contrast and size levels. We applied A 2 × 2 repeated-measures ANOVA for the contrast level (% 2 and % 99) and size (1.67 and 9.05 degree) as factors. The

results revealed a main effect of contrast on the BOLD activity ($F(1,5) = 15.392$, $p = 0.011$), as well as a main effect of size ($F(1,5) = 23.929$, $p = 0.005$). However, results revealed no effect of interaction involving size and contrast ($F(1,5) = 1.237$, $p = 0.317$).

Paired samples t-test showed that V3ab activity increased significantly with size at low contrast (for small stimuli: M = -0.07, SEM = 0.08; for large stimuli: M = 0.36, SEM = 0.10; $F(1,5) = 4.24$, p = 0.008), and V3ab activity increased significantly with size at high contrast as well (for small stimuli: M = 0.05, SEM = 0.08, for large stimuli: M = 0.81, SEM = 0.31; $F(1,5) = 3.06$, p = 0.03). Similar to V1, these results show that V3ab activity increased with size, and the amount of change is greater when the stimuli have high contrast.

3.1.4 Discussion

In this experiment, we measured the activity patterns at the cortical regions that are known to play a significant role in visual motion information processing. We found that the activity patterns measured at V1 and MT+ were differentiated in response to contrast-size interaction in motion perception. At MT+, neural responses of center-surround neurons were enhanced when the low-contrasted stimuli increased in size, and remained the the same when they have high contrast. On the other hand, neural responses of V1 neurons increased with size if the stimuli have high contrast, and remained the same if the stimuli have low contrast. Therefore, these findings show that the behavioral effect observed with the psychophysics experiment were driven by the the center-surround receptive field organization of MT+ neurons.

Chapter 4

General Discussion

In the first part of the study, we measured the exposure duration thresholds for accurately judging the drift direction of peripherally presented Gabor patches in varying size and contrast levels. In line with the previous literature, we found that increasing the size of the stimuli decreased the duration threshold for accurately judging the drift direction if the stimuli have low contrast; and increasing size of the high contrasted stimuli resulted in increased duration threshold. In other words, observers required more time for accurately discriminating drift direction when the high-contrast Gabor patches gets larger, but less time when the low-contrast Gabor patches gets larger. In the second stage of the study, using a block-design fMRI, we measured activity patterns at visual areas V1 and MT+ in response to peripherally viewing drifting Gabor patches with the same spatial configurations used in the psychophysical experiment. Results showed that activity patterns measured at the two regions were differentiated. Activity of MT+ neurons that are responsive to the small sized Gabor patches (referred as center) significantly increased when it was surrounded by the low contrasted stimuli, which is in line with spatial facilitation of motion signals observed similarly in the literature [2]. Meaning, MT+ neurons coding the surrounding region facilitate the activity of neurons coding the center if the stimuli have low-contrast, compared to high contrast. At V1, however, BOLD activity evoked by the neurons encoding the center increased when the surrounding region had high contrast,

and remained unchanged with size when the stimuli have low contrast.

Activity patterns obtained from MT region are in line with the behavioral outcome we measured, however, results are at odds with the existing literature suggesting the involvement of similar center-surround receptive field organization at V1 during motion processing [54, 62]. Contrary to a spatial facilitation mechanism, we found that V1 neurons were not selectively responsive to small and large low-contrast stimuli, as the differences of activity for both sizes was found non-significant. On the other hand, activity in V1 increased significantly while the high-contrast stimuli increases in size, which is not what one would expect if the V1 neurons drive the decreased behavioral performance with increasing size at high contrast (spatial suppression). In other words, increasing size of high contrast stimuli resulted in neural facilitation at V1. Although previous literature found increased surround suppression with increasing eccentricity, we believe the observed discrepancy might be due to the differences in behavioral task. Our results, provide a evidence that V1 neurons that are encoding the periphery may have anatomically different center-surround receptive field organization than those encoding the fovea during motion processing [54, 62, 61]. Our results provided further evidence that the observed behavioral outcome are driven by the center-surround receptive field organization of MT neurons, not V1 neurons.

Neuronal mechanism of divisive normalization have been reported to underlie cortical responses of early visual areas [68, 69], and recent evidence showed a close association with this computational principle and center-surround antagonistic receptive field organization of neurons in both MT+ and early visual areas during contrast-size interaction in motion perception [62]. The divisive normalization model, when tested with our data, failed to predict the activity patterns measured at V1, while it successfully predicted the activity patterns observed at MT+, which is in line with the previous findings [62]. The observed discrepancies between the V1 data here and the findings in the literature could be twofold: the distinct difference in the choice of method for defining the sub-ROI, and/or the possible complex role of stimuli eccentricity in mediating the antagonistic surround organization of V1 neurons.

In Schallmo et al.'s study, they reported aggregated activity of V1, V2, and V3 (coined as early visual cortex (EVC)), while, we reported the V1 activity in isolation. In the literature, it has been shown that removing V1 and V2 activity reduces the neural suppression at V1 [70, 71]. Therefore, reporting the summed activity (EVC) may have 'obscured' the supposed suppressed V1 activity. Summed activity of multiple region, however closely linked they are, should not be compared with a sole activity embedded in the sum. Also, the difference of Gaussian model might not encompasses mechanisms of all V1 cells. In fact, there are a cluster of cell types (e.g. center-gated cells) that are selectively responsive to the stimulation of surround only, without stimulating the classical receptive field (CRF) (e.g. responsive to annulus presentation). This means, divisive normalization model may not encompass the working mechanisms of all neurons, and neurons that are triggered with foveal presentation and peripheral presentation could be different in nature. Considering the arguments listed above, we suspect the reason behind this disagreement could not be due to region of interests defined differently at both studies. In fact, V3ab activity bare strong resemblance to the V1 activity (see figure 3.10). Rather, the differences in the location of the Gabor gratings in both studies, hence the receptive field characteristics of V1 neurons for encoding the fovea and the periphery could drive the differences in V1 activity. Considering the strong resemblance in MT+ activity found at both studies, one can suggest that the receptive field properties of MT+ are insensitive to the stimulus position, and divisive normalization model successfully predicts the neural suppressive and facilitative mechanism of MT+ neurons. Although surround suppression strength and eccentricity has been investigated with electrophysiological recording at primate MT [36], and with behavioral experiments on humans [61], for future, neuroimaging studies systematically investigating the relationship between stimuli eccentricity and BOLD activity at both visual areas could be imperative.

As to bridge the data obtained by the method of psychophysics with the BOLD activity, we aimed to investigate the link between spatial suppression observed with behavioral performance and the surround suppression in the cortical area MT+. Previous neuroimaging research proposed the involvement of MT+ in

mediating the motion sensitivity performance [2, 62]. However, activity of early visual areas in isolation have not been analyzed for the primary reason of difficulties in drawing V1, V2, and V3 region boundaries. In the present study, however, we have successfully avoided the issue of foveal confluence by presenting the Gabor patches at the periphery while viewers maintained fixation at the center of the visual stimulation field. This setup allowed us to localize V1, as well as MT+ within a run. Although we observed heightened sensitivity in V1 BOLD signal compared to the MT+ for both contrast levels, we suspect that narrower receptive field sizes of V1 neurons naturally led to this outcome [72].

4.1 Feedback - Feedforward Interactions

Surround suppression in response to drifting motion contrast have been reported to occur in primate V1, a finding that is inconsistent with ours [54]. However, as V1 is a hub within a vastly interconnected network, there is little doubt that the nature of surround modulation activity in V1 is influenced by the interplay between V1 and higher visual areas [73]. In fact, feedback from MT influencing contextual modulation related activity in V1 have been reported in the literature [74, 75, 76, 77]. In Ponce et al's study indirect pathway from V1 to MT via V2 and V3 have been investigated while awake macaques engage in visual motion and depth processing. Selectively cooling V2 and V3 resulted in decrease in activity at MT and disruption of the disparity tuning of MT neurons [75]. Considering the findings suggesting the contrast-independent involvement of V2 and V3 [74, 71, 70], the differential contextual modulation in V1 activity in response to differing contrast levels [54], and the high contrast sensitivity found in MT+, [78, 79, 80, 81] V1 activity could possibly be influenced by the feedback received from MT+. Anatomical observations exploring the center-surround receptive field organization of layers within the primary visual cortex could highlight the role of the center-surround cells in input and output relationships. Similar approach have been taken in the literature investigating the receptive field organization of the neurons located at different layers of the macaque MT. They show that, neurons located at the input layer of the MT do not have center-surround

receptive field organization [43, 28]. Present study's objectives are not covering the tripartite interaction between stimuli eccentricity, receptive field sizes and the antagonistic motion surrounds. Therefore, additional experiments that are specifically designed to investigate this intricate mechanism are needed. Considering the similarity of activity patterns of V3ab with the primary visual cortex, the inhibitory center-surround interactions appear to originate at MT+ area. However, to understand more about the feedback-and feedforward interactions between V1 and higher cortical regions, studies done with EEG, and causal investigations with fMRI (e.g. with Granger causality method) could be imperative.

4.2 Limitations

Intuitively, one could expect to observe complete match between BOLD activity and behavioral performance, if MT+ is the region responsible for driving the observed behavioral effect. Such as, increased behavioral performance should match with increased MT+ activity (consisted with spatial summation), and decreased behavioral performance should match with decreased MT+ activity (consisted with spatial suppression). Although, increase observed in MT+ activity was paralleled with enhancement of the behavioral performance when the low-contrasted stimuli increase in size, MT+ activity remained largely unchanged while the behavioral performance deteriorates when the high-contrast stimuli increase in size. We believe the observed discrepancy could partly be due to MT activity saturating at a certain contrast level, and non-linearities in the BOLD signal. In fact, when the effect of contrast level is indexed with size, we found that the amount of change in MT+ activity in response to increasing stimuli size is greater if the stimuli have low contrast compared to high contrast, which is consisted with the behavioral effect. It is also likely that suppressed information observed at MT+ could be sent to the higher cortical areas for more complex visual motion processing via efferent connections. There are examples of this type of mechanism in the literature. Studies showed that non-perceived visual information (e.g. with crowding and binocular rivalry) can still affect the visual motion processing and visual awareness, which shows that further processing are done at higher cortical

regions [82, 83, 84].

The methodology we adopted for defining the sub-ROI could also explain some part of the question of why high contrasted surround caused no significant suppressive influence to the neurons encoding the center. In the present study, in order to define the sub-ROI, we deducted the activity evoked by small sized grating from the activity caused during no visual stimulation (see Methods for details). Therefore, this approach cannot disregard the neurons with larger receptive fields that encompasses both small and large stimuli. Because our method allow for these types of neurons, we might have drawn our sub-ROI border larger than it should be. One can take a more parsimonious approach by identifying areas that are responsive to larger stimuli, then deduct them from the areas selectively responsive to the small-sized grating, similar to what is recently done in the literature [62].

The observed contextual modulation of BOLD activity could partly be mediated by the BOLD activity given to the surrounding region. To circumvent this possible effect of increased BOLD activity due to the surround-only to the measured BOLD activity to the center, future studies should add a control condition for identifying regions that are responsive to the surround only. One way to achieve that would be to use an annular shaped stimuli (e.g. a ring grating), then deduct the regions that were activated by that stimuli from the region evoked by the small sized grating. In other words, the resulting BOLD activity given to the annulus shaped stimuli can be deducted from the BOLD activity measured for the center. In this way, one can eliminate the possibility of involvement of surround-related BOLD activity from the activity related to center-surround interactions.

Another reason for the observed no-change in increasing size of high-contrast at MT+ activity could be due to the balancing out of decreased cellular excitation activity with increased cellular inhibition activity. However, a recent study proposed that neural suppression is not mediated by GABA-ergic neural inhibition activity -an inhibitory mechanism that is orchestrated by the primary inhibitory neurotransmiter GABA [62]. Therefore, neural excitation could be the result of

inhibition of neural inhibition mechanism, which could led to increased cellular activity, rather than a decrease in activity. Although resolving this issue puts pressure on the limits of the fMRI as a method, experiments using physiological methods such as EEG, and electrode recordings could possibly provide insightful findings to resolve the involvement of excitatory and inhibitory neural mechanism in motion processing.

In the fMRI experiment, observers did not engage in the behavioral task as they did in the behavioral experiment. This might raise concerns as to validity of comparing the BOLD activity with the behavioral performance. However, our results showed that merely exposing the individual to the peripheral visual stimulation while they were fixated at the center of the visual field was found to be robust enough to observe the effect of the experimental manipulation. In fact, at the beginning of this study, we asked observers to distribute attention to the peripherally presented Gabor patches with a very similar task that was used in the behavioral experiment inside the MRI. We found negative BOLD responses around the cortical areas of V1 and MT+, which hindered the investigation regarding the surrounding region. Therefore, we changed to paradigm to the one used in this study. However, the role of attention in changing the receptive field organization of cortical area MT is not unknown [85]. Still, we argue that the effect of attention to the center-surround interactions observed at MT+ would be marginal when tested with our paradigm.

We observed that fMRI BOLD activity for MT+ region became negative for the small low-contrasted stimuli. We argue, the stimuli used in this study was low in saliency, therefore, it might be filled in with the surrounding area, thus reduced the visibility when viewed at the periphery. Although, this is still a possibility, further inspection of the timecourse data of MT+ in figure 3.5 reveal that pre-period volumes used for the baseline for the computation of percent signal change might contributed the observed negative signal change. In other words, pre-period event related averaging, if defined as the average of one volume prior to the onset (-1) and volume at the onset time (0), would shift the timecourse data of MT+ towards more positive values. Therefore, observed negative values at MT+ for the small sized low-contrasted patterns might partly be due to the pre-period volumes

chosen for computing the baseline. Still, it would be imperative to systematically analyze the effect of saliency in fMRI BOLD signal.

4.3 Implications of the study

The spatial summation and suppression characteristics of the visual coding mechanism have been attributed to various clinical settings. Decreased spatial suppression have been associated with schizophrenia [86], senescence [79], and overall intelligence [64]. Locating the cortical region involved in mediating the perceptual outcome can contribute to the investigations in elucidating the cause of this phenomena. Neuroimaging studies like this can pinpoint the regions that need to be analyzed with a molecular scope. More research in this area will hopefully aid the early diagnosis methods for schizophrenia, as well as of the early diagnosis methods for the aging brain symptoms. Insights gained from these studies could be used as novel treatment methods for tackling the aging problems and schizophrenia related disturbances of individuals as well.

4.4 Future Directions

To further elucidate the role of stimuli salience in mediating the contrast-size interaction of center-surround MT+ neurons, one can systematically manipulate stimuli salience and investigate the changes reflected at the cortical area MT+ with fMRI. One line of research suggest that low stimulus saliency (low contrast, noisy stimuli) calls forth neurons encoding the global motion with larger receptive field sizes in order to enhance the sensitivity of the visual system for better detecting the stimuli ([47]. On the other hand, when the stimuli is salient enough (e.g. high contrast), local motion units are operating with much accuracy, therefore, suppression is necessary to save energy [87]. The extend of the influence of the stimulus saliency could be put up to test by breaking the high contrast stimuli (high salience) into many pieces, hence lowering the stimulus salience

without changing the contrast level. The neural suppression usually observed with increasing the size of the high contrast stimuli should be reduced when the saliency of the stimuli lowers down. One can explore other saliency factors' role in center-surround interactions observed at MT+. Triggering the local-motion integration activity with the stimuli strength and measuring it with fMRI response would further elucidate the mechanism involved in center-surround interactions in motion perception.

Another line of research can test the role of stimuli edges in mediating the center-surround interactions. In the literature, Gabor patches are used with gradual spatial envelope mask applied on it, making the edges of the Gabor blurry. This setup influences the neurons that are encoding the edge to become less suppressed, therefore the contribution of the neurons that are encoding the edge are minimized. Tadin's personal observation suggest that when the stimuli edges become non-blurry, increasing the size of the stimuli do not diminish the perceptual performance [60]. One can test the above mentioned speculation with an fMRI study. Would the spatial suppression reduction observed when using non-blurry edged stimuli are reflected with increase in MT+ activity? Investigations focusing on the responsiveness of the MT+ activity to the behavioral outcomes will further strengthen the argument that neurons at MT+ have center-surround coding characteristics.

4.5 Conclusion

This study, for the outcomes listed above, provided further evidence that the behavioral outcome of spatial suppression is driven by the antagonistic receptive field organization of the groups of neurons located at the cortical area MT+. Future research investigating the involvement of MT+ activity to the contextual modulation at the cortical area V1 would be imperative for shedding more light on the horizontal and vertical feedback-feedforward connections between V1 and MT+. All in all, present data provided further neuroimaging evidence that the spatial summation observed with the behavioral performance generated de novo

in MT, and possibly projected to lower levels for optimizing neural coding.

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