Motion Processing of Reverse Phi

by

Mohana Kuppuswamy Parthasarathy

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EXAMINING COMMITTEE MEMBERSHIP

The following served on the Examining Committee for this thesis.
The decision of the Examining Committee is by majority vote.

External Examiner	Dr. Patrick Bennett Professor & Canada Research Chair, Department of Psychology, Neuroscience & Behaviour, McMaster University
Supervisor	Dr. Vasudevan Lakshminarayanan Professor, School of Optometry and Vision Science, University of Waterloo
Internal Members	Dr. Daphne McCulloch Professor; School of Optometry and Vision Science, University of Waterloo
	Dr. Kaamran Raahemifar, Professor, University of Waterloo
Internal-external Member	Dr. John Zelek, Associate Professor & Co-Director VIP (Vision Image Processing) Lab, University of Waterloo

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STATEMENT OF CONTRIBUTIONS

I, Mohana Kuppuswamy Parthasarathy, was involved in the concept/design of the thesis projects, data collection data analysis, article writing and article editing. My supervisor, Dr. Vasudevan Lakshminarayanan was involved in concept/design of the projects and in article editing.

The candidate certifies that:

- The above statement correctly reflects the nature and extent of the candidates contributions to this work, and the nature of the contribution of each of the co-authors; and
- The candidate wrote all or majority of the text.

Abstract

Introduction:

When the contrast of the successive images is reversed for a target in an apparent motion stimulus, the perceived direction is reversed, i.e., opposite of phi motion, which is an integration of the sequential position. This phenomenon is called reverse phi. It is believed to be processed through the interaction of ON and OFF pathways. We investigate the following aspects of this phenomenon.

Aims:

- Experiment 1 (Chapter 2): To measure the spatio-temporal characteristics and motion coherence thresholds of reverse phi and compared to those of phi motion.
- Experiment 2 (Chapter 3): To measure the spatio-temporal characteristics and motion sensitivity at the central and peripheral presentations of reverse phi and phi motion
- Experiment 3 (Chapter 4): To test the inhibition hypothesis of reverse phi motion using transparent motion stimuli.
- Experiment 4 (Chapter 5): To investigate whether contrast reversals had an effect on the perceived speed.

Methods:

All experiments were conducted in 10 participants using random dot kinematograms (RDK). Reverse phi stimuli consisted of dots changing from one contrast polarity to another upon displacement. Phi stimulus maintained the same luminance polarity throughout the trial.

- Experiment 1 (Chapter 2): The temporal intervals tested varied from 16.7 to 66.8ms in steps of 16.7ms. The spatial displacements tested ranged from 0.1 to 0.5 deg, and for 16.5ms and 33.4ms, and the displacements were extended to 1.35 deg. For motion coherence thresholds, the signal dots were varied from 0 to 100% in variable steps for phi and reverse phi motion. Subjects reported the direction of motion.
- Experiment 2 (Chapter 3): RDK stimuli were presented at the fovea and the superior retina at 15deg eccentricity. The dot size was 0.13° for central stimulus, which was scaled up to 0.26° for peripheral presentations. The temporal intervals tested varied from 16.7 to 50.1ms in steps of 16.7ms. The spatial displacements tested ranged from 0.1 to 1.35 degrees. For motion coherence

thresholds, the proportion of signal dots was varied from 0 to 100% with different step sizes for phi and reverse phi motion. Subjects reported the direction of motion.

- Experiment 3 (Chapter 4): In the motion transparency experiment, two RDKs moved in the opposite directions at 100% coherence. The subjects had to report the direction of motion whether it was in the right diagonal or left diagonal direction. In the motion nulling experiment, phi and reverse phi motion moved in the opposite directions with a fixed number of reverse phi dots and varying number of phi dots. The subjects had to report the direction whether the dots moved in the left, right or in both directions.
- Experiment 4 (Chapter 5): Two RDK stimuli were presented for 0.5 second each in a sequential order with an inter-stimulus interval of 200 ms. First interval contained the standard stimulus with one of the following speeds - 18 deg/s, 24 deg/s or 34 deg/s and the second interval contained the test stimulus, which was 50%, 70%, 100%, 120%, 145% and 200% of the standard speed. The subject's task was to compare the speed of the two stimuli and indicate which of the two stimuli appeared to be faster. Four conditions were tested with phi and reverse phi motion being test and/or standard stimulus.

Results:

- Experiment 1 (Chapter 2): The optimal spatial offset in sequential images for reverse phi and phi motion was 0.3 to 0.5 deg. The optimal temporal offset was 16.7ms for reverse phi and 16.7 or 33.4ms for phi motion. The average coherence threshold for reverse phi (25.9±6.7%) was higher than that of phi motion (14.5±3.2%), but the difference was not significant when stimulus parameters were considered.
- Experiment 2 (Chapter 3): Reverse phi was observed both in central and peripheral presentations. There was no difference in the percentage correct responses between central and peripheral presentations for phi and reverse phi, except at 0.1 and 0.4 deg spatial offsets of 33.4ms temporal interval where reverse phi was perceived better at the periphery at 0.1 deg and at the center at 0.4deg. There was no difference in the motion coherence threshold between central and peripheral presentations for either phi or for reverse phi motion.
- Experiment 3 (Chapter 4): Subjects confirmed perceiving a reversed direction for a reverse phi stimulus using single RDK. In motion transparency experiment, subjects reported perceiving motion along the direction of stimulus displacement for both motion stimuli. In the motion nulling experiment, reverse phi motion was dominated by a much smaller phi motion signal.

- Experiment 4 (Chapter 5): The speed discrimination thresholds for phi motion were 5.8, 7 and 8 deg/sec for the standard stimuli of 18, 24 and 34 deg/sec, respectively. It was not possible to obtain a speed discrimination threshold for reverse phi motion because slower test speeds were perceived as faster than the standard speeds and vice versa except for the 18deg/sec standard speed, where faster test speeds were perceived as slower. When reverse phi and phi motion were compared, reverse phi was perceived as faster in 93.3%±4% of the trials when the phi motion was of the same speed as the reverse phi, despite changing the order of the presentation.

Conclusions:

- Experiment 1 (Chapter 2): The spatio-temporal characteristics of phi and reverse phi motion largely overlap. This indicates that a common mechanism, short-range system, processes the two types of motion. However, processing higher level tasks that involves segregation of signal from noise shows that reverse phi is less salient.
- Experiment 2 (Chapter 3): Although there are anatomical and physiological differences between the center and periphery, the motion signals of reverse phi are processed equally well at the fovea and the retinal eccentricity tested.
- Experiment 3 (Chapter 4): In reverse phi motion, transparency motion was perceived rather than an orthogonal motion. This suggests two possible conclusions: 1) there is no inhibition caused by a reverse phi motion on neurons tuned to the direction of physical displacement suggesting that reverse phi follows evidence-only hypothesis at the low-level motion detectors, 2) if any inhibition was present, it was insufficient to elicit an orthogonal motion. The results of nulling experiment suggest that reverse phi is a weaker stimulus in the presence of regular phi motion
- Experiment 4 (Chapter 5): Slower speeds of reverse phi motion was perceived to be faster than the standard speeds due to the jerkiness inherent in the stimulus at slow speeds. The perceived speed of reverse phi was overestimated relative to phi motion when both were moving at the same speed.

The overall results suggest that the spatio-temporal characteristics of reverse phi are similar to that of phi motion, however, reverse phi is a weaker stimulus resulting in a lower sensitivity. Motion transparency is possible with reverse phi and with phi motion. Reverse phi is perceived as being faster than phi motion especially at smaller displacements.

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It is not only your actions that determine your future, but also someone else's. How you react to those actions also would have an impact. Life is a Domino! Everything happens for someone's good, if not yours sometimes! It is incredible how I decided to leave my country to do a PhD here!!? Well.. I don't want this to be a biography of my past 4 years. But I would like to acknowledge those who motivated me to take up this journey. I felt sad when Dr. L Srinivasa Varadharajan (our LSV sir), the head of the Department of Visual Psychophysics, Elite School of Optometry, left his job and moved to a better place. However, thanks to him!! I wouldn't have even thought about doing a PhD in visual psychophysics and perception if he had not left and if I was not given the opportunity to teach visual perception to my juniors in the master program. Thanks to Dr. Krishna Kumar (KK sir) for giving me that opportunity. Thanks to Dr. Vasudevan Lakshminarayanan (Dr. Vengu), my PhD advisor, for volunteering to train someone in visual psychophysics after LSV sir left. Again, thanks to KK sir for choosing me to be that someone! Life is, indeed, a Domino! Thanks to my husband at this point for making the decision for me to take up the offer and make that big move.

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List of Abbreviations

MT – middle temporal

LGN – Lateral geniculate nucleus

V1 – Primary visual cortex

RDK – Random dot kinematogram

MAE – Motion after-effect

ISI – Inter-stimulus interval

PSE – Point of subjective equality

Chapter 1

Introduction

This section lays out the background for the thesis by describing briefly the stages of visual processing followed by an overview of motion processing and its models. It includes a description of apparent motion, reverse phi motion, and a summary of the corresponding literature on the spatio-temporal characteristics, sensitivity, and the relation to the ON-OFF channels of visual system.

1.1 Visual Processing

Visual processing starts with the formation of an image of the visual scene by the optics of the eyes on the multi-layered neuronal layer of the eye, the retina (Figure 1-1). In the retina, multi-level processing happens starting with light absorption by the photoreceptors, which transfer the visual information onto bipolar neurons, which in turn transfer it to the ganglion cells. Other neurons such as horizontal cells and amacrine cells modulate the signals before being carried by the individual axons of the ganglion cells, which form the optic nerve. There is a considerable spatial filtering that occurs in the retina where the information from ~260 million photoreceptors is compressed into ~1.2 million fibers of the optic nerve[2]. These fibers project as different channels based on the neuron of origin such as magnocellular ganglion cells or parvocellular ganglion cells, ON or OFF cells, carrying specific information to the brain.

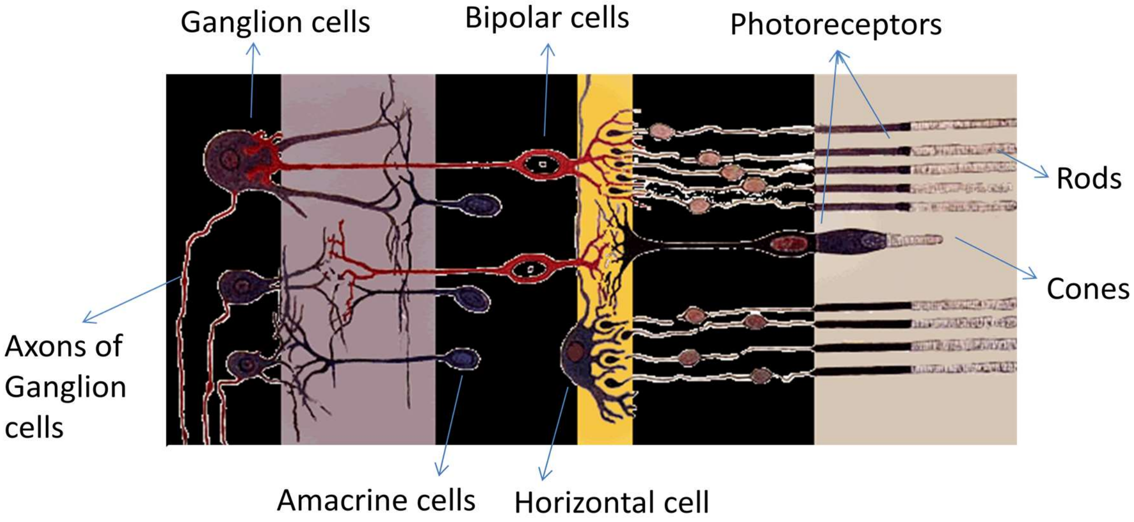


Figure 1-1 Schematic diagram of the retinal layers showing the organization of principal types of retinal neurons (Modified from https://en.wikipedia.org/wiki/File:Retina_layers1.gif)

The optic nerve fibers travel along two major divisions – retino-geniculo-cortical pathway and retino-collicular pathway (Figure 1-2). Retino-collicular pathway, which constitutes about 10% of the optic nerve fibers, as the name suggests, connect from the retina to the superior colliculus in the mid brain, which in turn connect to the pulvinar nucleus in the thalamus and then finally to middle temporal region (MT) at the posterior parietal cortex. The MT region is the extra-striate visual area that is involved in the analysis of visual motion[3,4]. The retinal ganglion cell layer also contains motion sensitive cells, which connect to the MT region directly via the retino-collicular pathway. This pathway is not only involved in 'blind-sight' but also in eye movements and visual attention[5,6]. The major pathway, retino-geniculo-cortical pathway, which constitutes about 90% of the optic nerve fibers carry the bulk of the visual information via lateral geniculate nucleus (LGN) in the thalamus to the visual areas in the occipital cortex. This thesis focuses on the motion processing aspects in the retino-geniculo-cortical pathway.

Once the fibers from LGN neurons synapse with the neurons in the primary visual areas of occipital cortex, V1, the processing becomes specific to form, color, and motion, therefore, the channels bifurcate into two major streams - dorsal and ventral pathway[7,8]. The dorsal pathway is referred to as 'where and how' pathway mainly serving as a 'vision for action' stream and projects its fibers to the posterior parietal cortex. Visual motion is processed primarily in this pathway. The ventral pathway is referred to as 'what' pathway serving as a 'vision for perception' stream and projects on to the inferior temporal cortex. Although there is a distinction in the core functions of the two pathways, they are heavily interconnected[9]. The complexity of the visual system is fairly simplified by the retinotopic organization of the visual areas. Adjacent areas of the visual field stimulate adjacent areas in the retina and in most other visual areas in the brain.

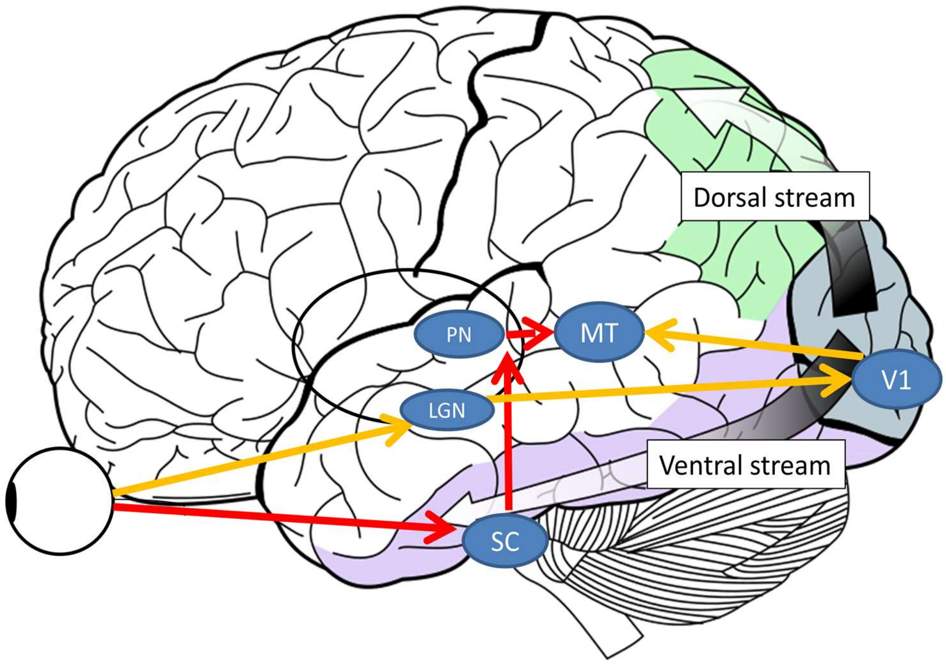


Figure 1-2 Visual pathway with retino-collicular pathway highlighted in red and retino-geniculate-cortical pathway in orange. From V1, the ventral and dorsal stream bifurcates to process what, where and how of the visual information, respectively. LGN – Lateral Geniculate Nucleus, V1 – primary visual cortex, MT – middle temporal, PN – Pulvinar nucleus, SC- Superior colliculus. (Modified from https://commons.wikimedia.org/wiki/File:Ventral-dorsal_streams.svg)

The functional organization of the neurons is reflected in their receptive field. The receptive field is the region in the visual field which affects the firing of a particular neuron when presented with a stimulus. The receptive fields of most neurons have an antagonistic center-surround organization, which could be excitatory or inhibitory. Visual information travels through ON or OFF channels, which starts at the bipolar layer of the retina and converges at the visual cortex. An ON-center cell responds with excitations when light falls on its receptive field center, however, it responds with inhibitions when the light falls on its surround region (Figure 1-3). The OFF- center cell has the opposite responses at its center and surround. A detailed explanation on the ON and OFF cells in the retina and their functions is given in section 1.5. The receptive field shape determines the ability of the neuron to respond to the motion stimulus. As the retinal ganglion cells and LGN neurons have circular receptive fields, they are not very sensitive to motion. Each neuron in the downstream of the visual pathway integrates the receptive field of the preceding neurons that connect to it, thus having a larger and generally more complex receptive field. The neurons in the cortical areas have elongated receptive fields, which make them sensitive to the direction of motion. Therefore, the first direction sensitive cells are found at the V1 region [10,11,12].

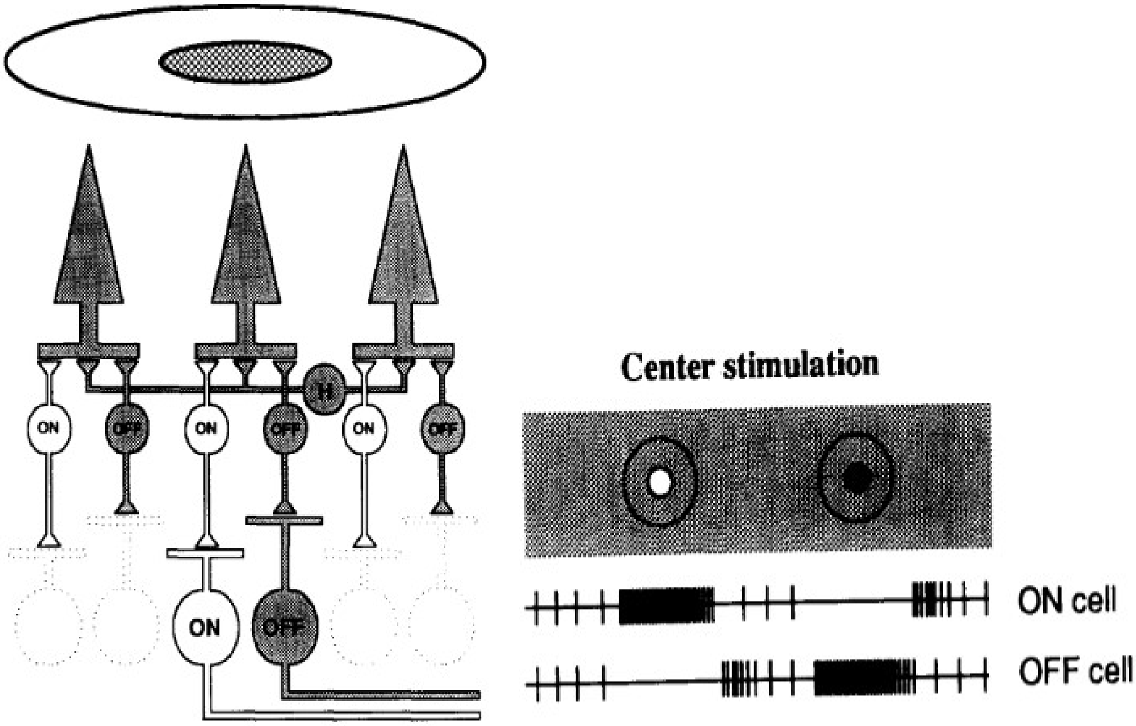


Figure 1-3: Left - The anatomical organization of ON and OFF channels within the retina and the receptive field. Right – Electrophysiological recordings from ON and OFF cells when light is present/absent at the center of the receptive field. ON cells give excitatory responses to light stimulation at the center whereas OFF cells give inhibitory response. (From Schiller, 1992[13])

V1 or the primary visual cortex or the striate cortex consists of simple cells and complex cells, which receive their inputs from LGN. Simple cells have linearly oriented receptive fields with distinct excitatory region flanked by inhibitory regions. Most of the complex cells which receive their inputs from simple cells have indistinct receptive fields and therefore show spatial invariance. Both types of neuron are orientation selective and a subset motion direction selective.

1.2 Motion Processing

Motion perception is an important function of the visual system that is necessary for survival and navigation through the dynamic environment. Motion is defined as a change in the object's position with time, which causes luminance changes across the retina over time. In order to detect this motion, the motion sensitive cells correlate the luminance changes at different spatial and temporal frequencies. Visual motion is represented in independent channels within the dorsal pathway[14,15], each of which is tuned to a certain spatial-temporal frequency band[16,17].

In general, motion perception is dependent on the response of direction-selective neurons, i.e. neurons that are differently sensitive to various directions of motion[18]. The low-level motion detection occurs at V1 where the first direction sensitive cells are found. The simple and complex cells present at V1 have smaller receptive fields relative to the higher order cortical neurons that limit the motion detection to local details. Therefore, V1 cannot provide an accurate sense of the global motion of an object - a limitation called the aperture problem. These local details are fed into the MT region of the brain via a hierarchy of extra-striate visual areas[19]. The MT area, which is implicated in the processing of motion and is the first extra-striate area that integrates motion information[11], is located at the caudal edge of the superior temporal sulcus on both the hemispheres of the brain[18,20,11] (Figure 2). From MT, the information is transferred to the medial superior temporal (MST) region for further processing [21, 22–24]. The MST region processes complex motion such as optic flow involving expansions, contractions, and rotations[25,26]. Both MT and MST have larger receptive fields, which enable the integration of the local motion directions across different spatial-temporal frequency channels that are associated with a common object and segregate the ones that belong to other objects, thus providing a global percept.

MT has direction selective neurons arranged in a columnar fashion and each neuron is tuned differentially to a broad range of directions (~100° tuning width[27]) with its peak sensitivity to what is called preferred direction[28,29,30]. They also have an anti-preferred direction or null direction, which is opposite to the preferred direction, to which the neuron responds by inhibition[27,21,31,32]. This is called motion opponency and it arises from the directionally selective neurons tuned to the opposite direction. The MT responses to the preferred direction was 5-10.9 times more than the null direction[21,23]. MT neurons exhibits more motion opponency than V1 neurons[33,34].

Motion processing involves not only discerning the direction of motion but also the speed[12]. MT region has speed-sensitive cells that have preference to certain range of speeds. The peak speed preference of MT neurons is 32deg/sec with a range from 2 to 256 deg/sec[21]. Electrophysiological studies have isolated many MT neurons particularly at the foveal representation that are sensitive to slow speeds. Neuropathological studies have also shown that lesions at brain areas including MT and MST affected direction and speed discrimination[35].

1.3 Apparent motion

1.3.1 Definition

A moving object creates visual images that drift on the retina. But a sense of motion can be perceived with two static objects and this type of motion is called apparent motion or illusory motion [36,37,38,39,40]. Most stimuli used in testing motion evoke the percept of apparent motion. When two similar static objects are presented alternately at a sufficient spatial shift and an appropriate time interval, apparent motion, i.e., perception of a single object moving back and forth, is observed[36]. This is achieved by correlating the corresponding local points of the object for matching brightness[39].

1.3.2 Types of Apparent Motion

The perceived apparent motion depends on the temporal interval between the two static objects. As the temporal interval decreases, the perception of the static objects changes from succession to flicker, to smooth apparent motion, to simultaneity[37,41,42]. When the two static objects are shown one after the other with appropriate spatial offset and temporal separation of about 60ms, Beta movement, i.e. a single object moving from point A to point B, is perceived. When the temporal interval is between 30 and 60ms, the motion is perceived without any persisting object, this type of apparent motion is called 'pure phi'. There is another type of apparent motion called Delta movement, which is the reverse of beta movement where the movement is seen from the second object to first. This reversal of direction is accomplished by changing the intensity of the second object with respect to the first. The definition of phi motion and apparent motion has been confusing in the literature [43]. In this thesis, phi motion is defined as a type of apparent motion perceived as a smooth continuous motion when discrete objects are presented with appropriate temporal and spatial offsets.

1.3.3 Short versus Long –range Motion Processes

Braddick[44,45] proposed that motion perception happens through two motion mechanisms – short range and long range. According to the author, the short range or first-order motion system is an early motion process that extracts motion when the spatial offset is < 15 min of arc and temporal offset of 100ms or less. This low-level processing requires clear similarities between the involved objects in terms of the luminance. On the contrary, long range or higher-order motion system processes apparent motion when the spatial and temporal offset is >15 min of arc and greater than 100ms, respectively. A subtle similarity between the objects, in terms of orientation, luminance, color, etc, is sufficient to process motion in this system and is thought to occur in the higher centers not involving the low-level motion detectors. In short, stimuli with short jump size and absence of inter-stimulus interval (ISI) stimulated short range and stimuli with large jumps (with or without ISI) and ISI conditions stimulated long range[46]. Hence, the motion perception with random dot kinematograms decreases for larger spatial displacements and longer ISIs. In a 2 frame experiment containing black and white dots, Anstis and Mather[46] found that same-polarity jumps i.e., white dot moving to white and black dot moving to black occurred when the jump size was as small as 10 min of arc, however, when the jump size increased to as much as 1 deg, the white spot appeared to split and move towards both white and black spots. This implies that short range is sensitive to luminance polarity change while long range system is not.

These two mechanisms are related to the popularly known first-order and second-order mechanisms of motion processing[47,48,49]. First order motion mechanism processes stimuli that have differences in luminance or color while the second order motion system processes stimuli that vary in contrast or texture. A third order motion system has also been proposed by Lu and Sperling[50] that relates to feature-tracking. Cavanagh and Mather[47] suggest that although there are different visual stimuli (first order and second order) that these motion systems respond to, they have a common mode of operation.

1.3.4 Motion models

Several models exist for describing the short and long range motion mechanisms. They are broadly classified into models that use feature-tracking and models that use intensity change. The feature tracking models, as the name suggests, identify the object/feature and track it for a certain period of time thereby extracting the velocity of the object. They describe the long range mechanism involving higher level processing[51]. On the other hand, intensity-based models look for changes in light intensity over space and time thereby obtaining the direction and speed of the object. In intensity-based models, there are different ways of capturing the spatio-temporal intensity changes. The gradient method obtains the velocity of the object without taking the stimulus structure into account[52,53]. Correlation-based models look for spatio-temporal correlations to extract motion information. In the following paragraphs, correlation based models are discussed.

The correlation scheme of intensity based models involves three-stages. In the first stage, the pre-processing of the motion information takes place involving the spatio-temporal filters at the retinal level. The characteristics of these filters such as the spatial separation determine the tuning properties of the motion detector units. The next stage involves local motion detection. In the post-processing stage, the local motion signals are integrated into a global motion percept. Another stage involving local motion pooling was suggested in between the local motion detection and global motion integration to explain the perception of motion transparency[34,54], however, this idea has been opposed by some studies[55].

The basic unit of a motion detector consists of two receptors separated by a specific distance, a delay unit and a correlator[56] (Figure 1-4). When an object is presented at the receptive field A, it sends its signal to the correlator with a delay, then, the object moves to the receptive field B and produces a similar signal without a delay. This temporal filtering could happen at LGN or V1[57–59]. In the next stage, when the correlator receives the inputs from both receptive fields at the same time, it will produce an output signal. The spatial separation of the receptors and the temporal delay determine the speed tuning of the particular motion detector unit. The orientation of the receptors determines the direction tuning of the detector unit. In a motion scene consisting of different directions and speed, multiple motion detector units with different spatially separated receptors, delays and orientations are compared and combined to provide a global percept, which occurs at the higher hierarchy of motion system. This basic arrangement of the motion detector unit is used in the popular models such as Reichardt model[60], and models in humans and non-human primates such as motion energy model[61–63].

1.3.4.1 Reichardt's model

Reichardt's model[60] is one of the earliest models to describe the processing of a moving object to infer its direction of motion. It was originally developed to obtain the tuning responses of insects to moving patterns. An elaborated version of Reichardt's model[62] was described for human motion perception consisting of two local motion detectors (Figure 1-4), which work in the way described in the previous section. It correlates the inputs from two receptors separated in space – one with a temporal delay, which is equivalent to the time taken for the object to move from receptive field A to the receptive field B – by multiplying them together. The other local motion detector performs similar correlation, but for the opposite direction. The output of the two local motion detectors tuned to opposite directions is subtracted and the direction of motion is deciphered by the sign of the output signal at the final stage of the model.

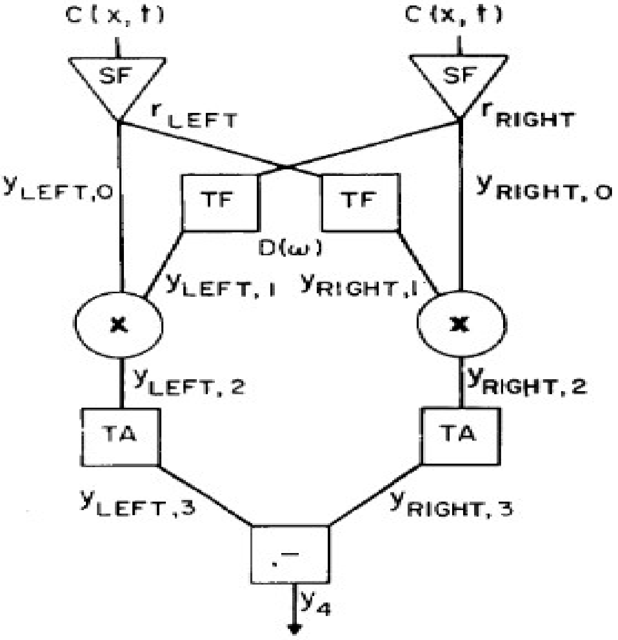


Figure 1-4 Elaborated Reichardt's model. Contrast information (C(x, t)) falls on the neighboring receptive fields, which are linear spatial filters, SF. Output responses from the each filter ($y_{LEFT,0}$, $y_{RIGHT,0}$) combine with the delayed output of the other filter ($y_{LEFT,1}$ $y_{RIGHT,1}$) at the respective correlator (X), which is tuned for right- or left-ward motion, to give out a signal ($y_{LEFT,2}$ $y_{RIGHT,2}$). The temporal filter (TF) causes the delay in the signal. In the next stage, the output signals ($y_{LEFT,3}$ $y_{RIGHT,3}$) from the two temporal integrators (TA) are subtracted to give an output (y_4) becomes selective for direction (Adapted with permission from van Santen and Sperling[64] © The Optical Society).

1.3.4.2 Motion Energy model

The motion energy model proposed by Adelson and Bergen[63] consists of two spatial filters each sending their output to two temporal filters, one of which has more delay than the other. Each combination of the spatial and temporal filter is known as the linear separable spatio-temporal filter that produces separable responses (Figure 1-5). The next stage involves combining the separable responses between the two spatial filters by adding or subtracting them in four oriented filters, two of which are sensitive to leftward motion and the other two to rightward motion. These responses are squared and added together to produce two local oriented motion energy which is directionally selective to opposite directions and independent of phase and contrast polarity. The motion opponent stage involves subtracting the motion energy responses from the previous stage.

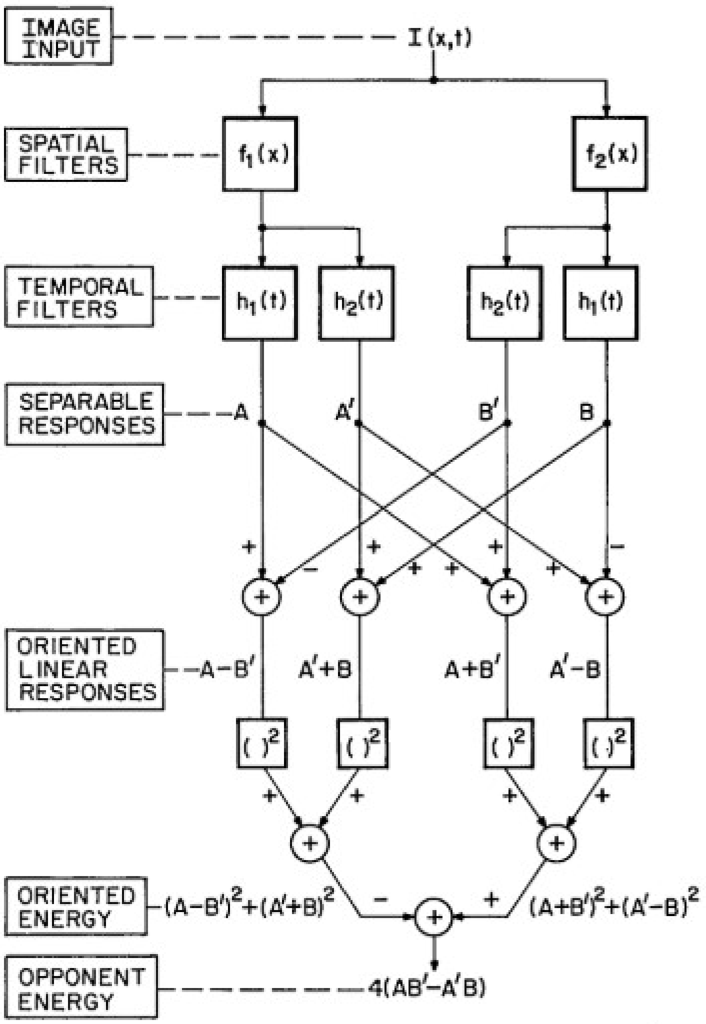


Figure 1-5 Motion energy model. The image input, I(x, t) passes through two spatial filters (f_1 and f_2). Each output then passes through two temporal filters (h_1 and h_2) where h_2 is more delayed than h_1. The output responses (A, A', B' and B) from these separable spatiotemporal filters are combined (by summing or subtracting) in four oriented filters to get oriented linear responses (A-B', A'+B, A+B' and A'-B). Two of these filters are tuned for leftward motion and the other two for rightward motion. The oriented motion energy is extracted by squaring the oriented linear responses and adding the output of each pair. Finally, the difference of the products AB' and A'B gives the final output. (Adapted with permission from Adelson and Bergen[65] © The Optical Society).

Motion is represented graphically in either Cartesian space or Fourier space (Figure 1-6). In the Cartesian space, a space-time plot is used to represent the motion direction and the speed. For an object moving to the right, a space-time plot would show a diagonal line to the right and the slope of the line would indicate the velocity. Changing the direction of the moving object in the opposite direction results in reversal of the diagonal due to the negative sign of the space axis. Larger displacements corresponding to faster speeds would decrease the slope of the line. In a Fourier space representation of the motion energy, the spatial and temporal frequencies are plotted and for the same object moving to the right, it would show a diagonal line in the opposite orientation and the slope would give the negative of inverse of velocity[66]. The type of representation or the motion model adopted depends on how the motion stimulus is described whether it is based on spatial displacement and temporal interval or on spatial and temporal frequencies.

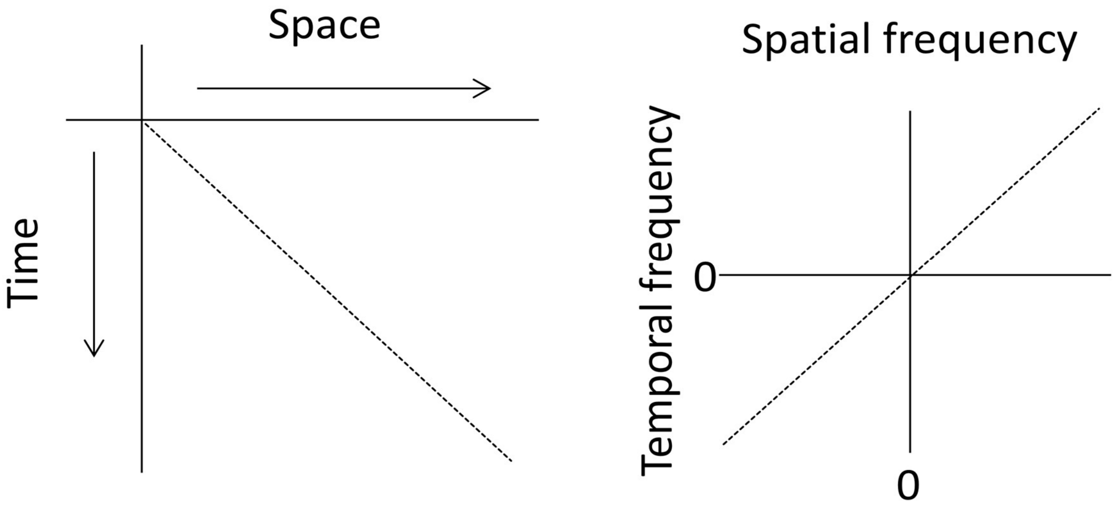


Figure 1-6 Rightward motion represented in Cartesian space (left) and Fourier space (right).

The final stage of motion processing which follows the local motion detection involves summation and integration. The local motion sensors tuned to different directions converge on to an integrator unit, which occurs at the opponency stage. From this, neurons with similar direction tuning excite an integrator neuron, while the rest of the neurons with quite different direction tuning would inhibit that integrator neuron and form the opponent direction unit. The output of this opponency stage feeds to the integration and segmentation stage for further processing to produce a global motion percept.

1.3.5 Correspondence Problem

In order to perceive a coherent motion between objects, each object element in one frame has to match with the corresponding element in the subsequent frame. How similar the successive objects should be in order to perceive apparent motion? This question was addressed by Ullman[67] who called it 'correspondence problem' which means that to be able to perceive motion, the visual system should know whether the object in the current frame corresponds to that in the preceding frame. Improper correspondence (in terms of luminance/contrast/spatial frequency) leads to ambiguous apparent motion. When the shifting object was of different spatial frequency, no apparent motion was observed[68]. In the next section, the consequences of reversed contrast in the subsequent frames of the moving object is discussed.

1.4 Reverse Phi Motion

It was discussed earlier that when two similar static objects are presented one after the other at an appropriate spatiotemporal interval between the two objects, it produces a phi movement, which is a perception of motion in the direction of the latter object. However, when the contrast of the latter object is opposite to that of the former, a reverse-phi movement is perceived in the direction of the former object, i.e, in the direction opposite to that of the displacement of the object[39] (Figure 1-7). This counter-intuitive phenomenon was identified by Anstis[39] when he presented a picture and its photo-negative one after the other with a slight spatial separation; he saw a phi movement in the direction opposite to the physical displacement. Reverse phi motion is observed not only for translational motion but also for rotational and radial motions[39]. The after-effects of reverse phi motion results in a motion perceived in the opposite direction to the reversed phi motion, which indicates that reverse phi is a true motion that is processed by a specific neural mechanism and is not simply a trivial stimulus-driven motion.

Reverse Phi is not similar to the delta movement, which is also a reversed perception of motion direction, but delta movement is due to the retinal delay and not the motion perception[69]. In delta movement, the first object is dimmer than the second object, which results in the first object being processed with a delay which could be >100ms, leading to the perception of the second object first followed by the first object.

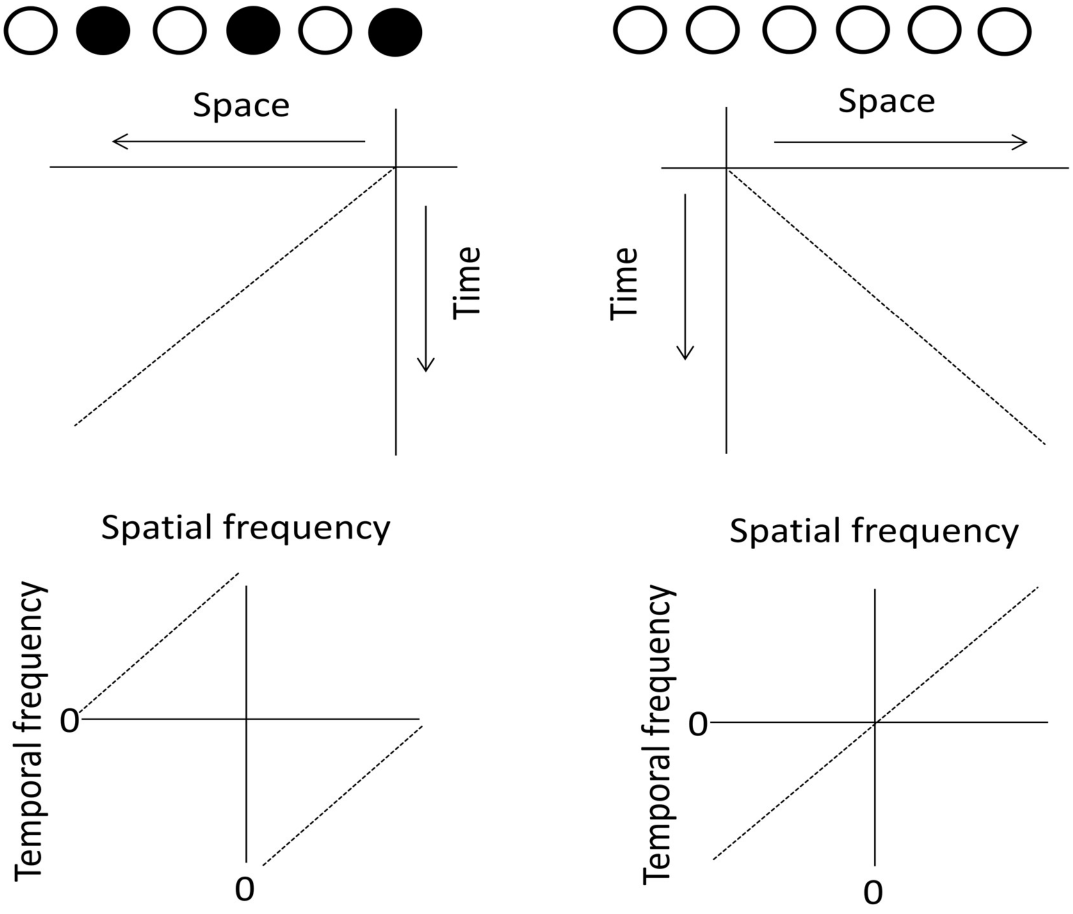


Figure 1-7 Reverse phi (left) versus Phi motion (right). Top panel: Contrast of the object in successive frames for reverse phi and phi motion. Middle panel: Space-time plots for reverse phi (leftward percept) and phi motion (rightward percept). Bottom panel: Fourier transforms of reverse phi and phi motion with motion energy at different quadrants indicating the reversal of direction of motion (Adapted from Bours et al.[66])

First order motion stimulus, which is a luminance based stimulus, is processed by the first-order motion units. Reverse phi stimulates both first order and second order motion units, but with opposing directions[70]. Reverse phi processed through first order units result in the reversal of motion direction. A second-order motion unit which involves full-wave rectification of the motion signals, would respond to the first order reverse phi stimulus as a forward motion rather than a reversed motion because the second-order or long range mechanism is unaffected by luminance polarity[43,46,68] An interaction between first and second order motion would give rise to no motion[55], which could be a reason why Edwards and Badcock[72] did not see a coherent motion in a contrast-inverting random dot pattern. A second-order motion stimulus is a non-luminance based stimulus, which requires additional processing steps to obtain the motion direction, therefore, a Reichardt's model does not respond to this stimulus[49]. An example of such a stimulus is a moving checkerboard with the checks containing random dots or uniform grey. The overall luminance of such a stimulus is a constant. Reversing between random dots checks and uniform gray checks resulted in the reversal of the perceived direction of motion[73]. Thus there are both first-order and second-order versions of reverse phi. A second-order reversed phi stimulus resulted in a forward motion at the central presentation (especially at low temporal frequency) and reversed motion at the periphery[74]. In our study, we used only first-order stimuli.

1.4.1 ON and OFF pathway

Since reverse phi motion involves two opposite contrasts, which is effectively carried by ON and OFF channels of the visual system, this section discusses in detail their anatomical organization and interaction between them.

1.4.1.1 Anatomical organization

In the visual system, there are many parallel pathways which work concurrently with varied degrees of independence. ON and OFF channels are one such parallel pathways that start from the retina at the level of bipolar layer and remain segregated through ganglion cells and lateral geniculate nucleus until they reach the occipital cortex[75,13]. Each cone at the fovea synapse with two bipolar cells, ON and OFF, each of which in turn synapse with the respective ganglion cells, so there are more number of ganglion cells than cones, which works well for the separate processing of information. ON and OFF cells have an antagonistic receptive field arrangement. In general, ON cells respond to light increments and have excitatory center and inhibitory surround whereas OFF cells respond to light decrements and have inhibitory center and excitatory surround[76–78]. The presence of two pathways to respond to light increments and decrements was thought to provide faster responses with excitations, low metabolic cost, and higher contrast sensitivity[13,77,78].

Slaughter and Miller[79] found that a compound named 2-amino-4-phosphonobutyrate (APB) blocks the ON cells by selectively hyperpolarizing the ON bipolar cells in the mudpuppy retina. Schiller et al.[78] found that pharmacological blockage of ON cells using APB in the eyes of mudpuppy, rabbit and rhesus monkey affected the processing of light increments but not light decrements suggesting that the pathways are largely separated in retina through lateral geniculate nucleus[13,77,78]. In addition, the ON surround of the OFF channel was not affected indicating that the center-surround organization of ON and

OFF cells do not arise from interactions between them. The two pathways converge their signals in the primary visual cortex which is evidenced by the blockage of ON cells, which did not alter the orientation and direction tunings at V1.

1.4.1.2 Differences between ON and OFF channels

Although the ON and OFF pathways follow the same route in the visual pathway, there are asymmetries in their anatomy and physiology that lead to differences in the psychophysical responses[80]. Electrophysiological recordings of retinal ganglion cells in macaque monkeys reveal that ON cells have about 30-50% larger receptive field size than its OFF counterparts probably because of which they have a faster response kinetics[80]. They not only respond to light increments but also capable of responding to light decrements unlike OFF cells which do not respond much to light increments. Psychophysical evidence to the perceived differences in light increments and decrements reveal that light decrements are detected faster and have lower detection thresholds than light increments[81,82]. In the central retina, there are more OFF center cells than ON-center cells and their representation at the cortex predominates that of ON-cells. Visual evoked potentials to dark stimuli are larger than the bright stimuli. Using line pairs and asking for the temporal order of the lines, Wehrhahn and Rapf[83] found that the threshold temporal delay for white line pairs was lower than that of black line pairs, concluding that the responses of OFF pathway is not equal to that of ON-pathway. However, there is evidence that higher order neurons of motion system such as those at MT[11], MST[84] and STS[85] are insensitive to the sign of the contrast of the stimulus, so whether the information is arising from ON or OFF pathway does not matter for higher order neurons.

1.4.1.3 Interaction of ON and OFF pathways: Psychophysical evidence

Although electrophysiological studies conclude that the signals from ON and OFF pathway merge at V1, many psychophysical experiments support the convergence of the two separate pathways somewhere in the visual pathway before the extraction of global motion, but not at the early visual pathway. Poor Vernier acuity with black and white lines, unequal width of black and white bars of a square wave grating after adaptation to rectangular wave grating suggest that dark and light information is separate in the areas that encode fine spatial locations[86] and size information[87,88]. For global motion task, Edwards and Badcock[89] showed that the ON and OFF pathways effectively combine their motion information to produce a global motion percept prior to the global motion extraction. They used random dot kinematograms with 50% white and 50% black dots and with the signal dots carried by both white and black dots, the threshold number of signal dots that gave a global motion percept was the same as the experiment in which the signal dots were carried by white dots only. This suggested that the integration of motion information from ON and OFF channels occurs before the global motion extraction stage. However, from the results of experiments with changing contrast polarity, they concluded that the ON and OFF pathways remain separate until the initial direction selective cells after which they combine into a single pathway before the extraction of global motion. When the moving signal dots changed polarity at every displacement, the threshold number of signal dots increased, suggesting that moving object with changing polarity is not an effective stimulus for the motion system and motion information cannot be extracted by combining alternating spatial temporal change from ON and OFF pathways. Edwards and Badcock[89] also found that the change the contrast polarity did not result in a motion signal in the direction of global motion or in the opposite direction. However, the spatial and temporal offset combination that was used in the study was not optimal for reverse phi to occur. Wehrhahn and Rapf[83] found that the threshold temporal delay was 2-4 times higher for line pairs of opposite contrast polarity than the line pairs of same polarity, suggesting that ON and OFF pathways do not converge at the early stage of motion processing. If they do, then similar threshold would be expected.

1.4.2 Mechanism of reverse-phi processing

A phi motion is achieved by correlating the corresponding local points of the object for matching brightness, however, for reverse phi, this brightness correspondence does not occur in the direction of physical displacement, hence the perceived direction of motion is the opposite direction[39]. For example, Figure 1-8 shows a regular checkerboard pattern presented at t1, and then displaced slightly to the right with contrast reversed at t2. According to Anstis[39], since the best motion correspondence occurs between matching nearest brightness, the perceived movement appears towards the left (opposite to the physical displacement). This explanation applies to a stimulus that is overlapping and spatially-periodic[49] such as a grating or a densely textured field[90]. We used a random-dot kinematogram stimulus with sparsely arranged dots, so this explanation of matching brightness would not apply[55].

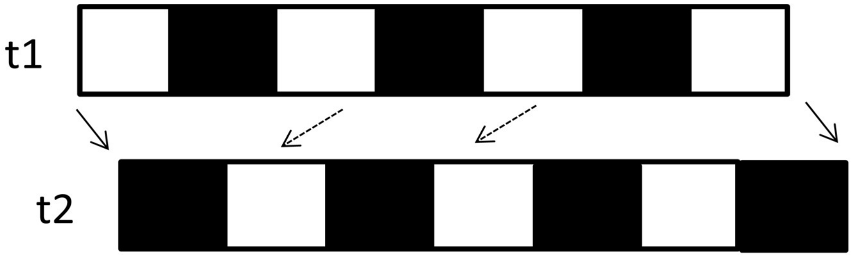


Figure 1-8 Checkerboard pattern shown at t1 and its contrast-reversed pattern shown at t2 with a small displacement towards the right. Nearest brightness matching gives a leftward motion. (Adapted from Anstis[39])

Reverse phi motion, a phenomenon opposite to the typical motion, is consistent with the well-known models of motion processing such as motion-energy model[65] and Reichardt detector[91]. In Reichardt's model, the contrast reversal generates a negative output at the correlator, which indicates an opposite direction of motion. As expected, a phi motion without any contrast reversal would give rise to a positive output. According to the motion-energy model, the contrast reversals in reverse-phi results in the motion or Fourier energy tipped towards the opposite direction, to which an appropriate motion detector would respond[64,65,92]. Therefore, the motion reversal was seen as trivial and it is simply due to the stimulus characteristics and not a different mechanism of motion detection[1,66]. It was not until Edwards and Badcock[93] who studied the interaction between the ON and OFF pathway that the connection between reverse phi and ON-OFF pathway was considered. Reverse phi motion was believed to be the result of interaction between ON and OFF cells at the lower level of motion processing[66,94]. The motion models do consider both ON and OFF signals that feed into the spatio-temporal filters to generate motion sensitivity. However, in those models, the spatio-temporal correlations occur within each channel independently and do not involve the interaction between the channels, i.e. ON cell response from one receptive field correlate with ON cell response from another receptive field and similar correlation in OFF channel. Studies have looked at the mechanism of processing of reverse phi motion and they propose the interaction between ON and OFF pathways to reverse the motion direction[66,93,95,94]. The two synergistic mechanisms are discussed here[94,95].

Let us take a motion detector that is tuned to left direction. When a stimulus moves leftward, the detector will show a positive excitatory response and it will show an inhibitory response for a stimulus moving rightward. For a reverse phi stimulus moving in the right direction, the activity pattern is reversed. The detectors (population response) may respond to the contrast reversals in the rightward direction in either of the two ways: 1) in the form of excitations which would be an evidence towards left (opposite direction to the stimulus), 2) in the form of inhibitions to the right (same direction as the stimulus), which would be a counter-evidence for left direction[96], both giving the perception of a leftward motion as opposed to the displacement of the target i.e., right direction of motion. The former (evidence model) was proposed by Mo-Koch[94] and the latter (counter-evidence model) was proposed by Bours et al.[95].

These two models of reverse phi motion incorporating the ON and OFF channels are useful for understanding this type of motion. Mo-Koch[94] proposed an arrangement of ON and OFF receptive fields with interaction/correlation between ON-center receptive field at one location and OFF-center receptive field at the other location. The same-contrast correlations (ON-ON and OFF-OFF) and opposite-contrast correlations (ON-OFF or OFF-ON) feed into the motion detection stage. The output of these four correlations had a positive sign (excitatory signal), which fed into the summation stage where there was excitatory response in the direction opposite to the physical movement. On the other hand, the same perceptual response is created in the opposite-contrast correlations could be having a negative sign i.e. inhibition, instead of a positive excitatory response, that feeds into the summation stage causing inhibition in the direction of the physical movement[95]. Both these models are similar in most parts except that there is a difference in terms of excitation and inhibition of directional motion detectors for reverse phi motion. Thus, reverse phi motion is due to either sensing the enhanced activity in the opposite direction neurons or the inhibitory activity in the same direction neurons.

Duijnhouwer and Krekelberg[96] recorded the tuning curves of V1 and MT neurons for reverse phi stimuli and phi stimuli and found that the V1 neurons respond according to counter-evidence model, whereas, MT neurons respond according to evidence model[1]. Bours et al.[95] tested behavioral responses to see if reverse phi was based on inhibitory or excitatory responses by presenting a transparent motion stimulus, i.e., two sets of dots moving in opposite direction, for instance, left and right, and found that the motion direction was orthogonal to the transparent motion, i.e., up and down[95]. This was also supported by the results of nulling experiment where a phi and a reverse phi motion moving in same physical direction cancelled each other, instead of appearing as transparent motion. Due to these behavioral responses, reverse phi motion was thought to behave like motion after-effects[95]. However, these behavioral findings contradict what we know about the close correspondence between motion perception and neuronal activity of MT[97]. Electrophysiological studies in the middle temporal region of macaque monkeys' brain have shown that reverse phi motion causes activation of neurons tuned to the direction opposite to the physical displacement[92,1]. In summary, the electrophysiological response of MT and behavioral response for reverse phi do not match. This raises the question whether V1 plays a major role in contributing to the reversal of the motion direction in reverse phi.

1.4.3 Spatio-temporal Characteristics - Phi

The motion system is sensitive to the spatial and temporal frequencies within a critical frequency window, outside which motion is not perceived[98]. In the space-time domain, the limit of the motion system is measured in terms of spatial offset and temporal interval [99,100]. A parameter that is commonly used to describe the limit of apparent motion perception is Dmax, the upper displacement limit or Braddick limit[44,101] which means the maximum distance over which an object can be displaced and still be perceived as a coherent motion. After this limit, the motion system cannot solve the correspondence problem and cannot segregate figure from background[101]. Wertheimer[37] and Korte[69] studied the optimal spatiotemporal offsets and stimulus durations necessary for perceiving apparent motion. Previous studies have used single dot, multiple dots, and gratings to study motion characteristics. Random dot kinematograms (RDK), designed by Julesz[102], became a popular stimulus after Braddick's study[44]. Braddick[44] found that the Dmax for RDK was about 15 min of arc. Using random dot patterns, the spatial and temporal limit was measured to be <0.2-0.3deg and 60-100ms, respectively[99]. Similar spatial separation and a much higher temporal limit was obtained by Fredericksen et al.[103]. The spatial separation and temporal offset selectively activates the motion detectors tuned to the particular spatial and temporal delays. There are many factors that affect the spatial-temporal limits of both reverse phi and phi motion for RDKs, the spatial characteristics being field size[90,104], dot size[44,90], retinal locus, and dot density.

The gradient model of motion discrimination by Marr and Ullman[52] can process both reverse phi and phi motion and according to this model, Hildreth[105] predicted that the displacement limits of both motion types should match. The motion-energy model of Adelson and Bergen[65] also alludes to the idea of a common mechanism underpinning phi and reverse phi motion processing.

Dmax for reverse phi motion was found to be 10 min of arc for foveal vision and 20 min of arc for peripheral vision[106]. These values are similar to those of phi motion, therefore, it was speculated that these motion types are processing through the same short range process. Previous studies have shown that the phi motion and reverse phi motion have similar spatiotemporal characteristics[49,90,107] and similar motion coherence thresholds[107], and therefore, should be mediated within a common short range process and does not involve higher order motion processes. However, the short range process is known to be sensitive to luminance polarity changes, which is the fundamental characteristic of the reverse phi stimulus. Therefore, we argue that reverse phi is processed through a different mechanism.

1.5 Gaps in the literature

What is known about reverse phi motion is that it causes reversed percept of motion direction, which is because of the inhibition of neurons tuned to the same direction, therefore, by disinhibition, the perceived motion is opposite to the physical displacement[95]. This inhibitory response arises at V1 due to the correlation between ON and OFF pathways, which respond to positive and negative contrasts of reverse phi motion. This inhibition at V1 causes excitation of MT neurons tuned in the opposite direction of physical movement. However, models of reverse phi predict an excitatory response following the correlation between ON and OFF neurons[94]. There are variety of mechanisms that may explain how the direction reversal happens in the visual system, although the perceptual outcome is the same.

It is well established that our motion percepts are based on the activity of MT. The tuning curve of MT neurons to reverse phi stimuli was found to be lower in amplitude and broader in half-height tuning width than for phi stimulus, which means that the reverse phi does not elicit a stronger and more directionally selective response compared to phi motion[96]. In addition, behavioral studies show that a slightly stronger phi motion (i.e., higher coherence level) was required to cancel the reverse phi motion of a particular coherence level[95]. Also, reverse phi motion elicits a lower proportion of correct responses than the phi motion even for 100% coherent stimulus[108]. These findings suggest a lower sensitivity for reverse phi stimuli. However, studies comparing the sensitivity of the two motion types have found equal sensitivity[107].

Reverse phi stimuli affect the direction of motion perception while both the speed and direction of motion have similar neural mechanism. There are some reports on reverse phi being perceived as faster at smaller displacements than at larger displacements[39,90]. But there are no quantitative studies on the effects of contrast reversals on the perceived speed.

1.6 Organization of the thesis

This thesis is structured as follows. Chapter 2 characterizes the two motion types – reverse phi and phi motion – based on their spatial and temporal limits and also describes the sensitivity of the motion system to these types of motion. Chapter 3 reports investigations into the effect of eccentricity on the spatial-temporal characteristics and the sensitivity of reverse phi and phi motion. Chapter 4 reports studies looking into the question of the possibility of the perception of transparent motion in reverse phi motion. In Chapter 5, the effect of contrast reversals in reverse phi on perceived speed is studied and whether there is any difference in perceived speed between reverse phi and phi motion is addressed. The final chapter summarizes the thesis and outlines future research directions.

Chapter 2

Spatio-Temporal characteristics and Sensitivity of Reverse Phi motion

2.1 Overview

2.1.1 Background

When the contrast of a moving pattern is reversed in successive frames, then the perceived direction of motion is reversed. This reverse phi phenomenon is believed to occur due to the interaction between the ON and OFF pathways. There is a considerable variability in whether these two parallel pathways converge at the early stage of motion detection or later. In this study, we looked at the spatio-temporal characteristics and motion coherence thresholds of reverse phi and compared with those of phi motion.

2.1.2 Methods

We measured the spatial and temporal limits of phi and reverse phi motion and their coherence thresholds in 10 participants using random dot kinematograms. The temporal intervals tested varied from 16.7 to 66.8ms in steps of 16.7ms. The spatial displacements tested ranged from 0.1 to 0.5 deg, and for 16.7ms and 33.4ms, and the displacements were extended to 1.35 deg. For motion coherence thresholds, the signal dots were varied from 0 to 100% in variable steps for phi and reverse phi motion. Subjects reported the direction of motion. The trials were presented according to the method of constant stimuli.

2.1.3 Results

The optimal spatial offset for reverse phi and phi motion was 0.3 to 0.5 deg. The optimal temporal offset was 16.7ms for reverse phi and 16.7 and 33.4ms for phi motion. The coherence threshold for reverse phi (25.9±6.7%) was higher than that of phi motion (14.5±3.2%), but the difference was not statistically significant.

2.1.4 Conclusion

The spatio-temporal characteristics of phi and reverse phi motion largely overlap. This suggests that a common mechanism, short-range system, processes the two types of motion. However, processing higher level tasks such as the motion coherence task, which involves segregation of signal from noise may possibly be inefficient with reverse phi stimulus and it shows that reverse phi is less salient.

2.1.5 Keywords

Reverse phi, phi, sensitivity, direction discrimination, spatial limits, temporal limits

2.2 Introduction

When the contrast of a moving object is reversed in the alternate frames, the direction of motion is perceived to be opposite to the direction of the physical displacement[39,106]. This counter-intuitive phenomenon called reverse phi was identified by Anstis[39] when he presented overlapping images of positive and negative contrasts of photographs. The reversal of the perceived direction of motion can be modelled as an imbalance of motion energy towards the opposite direction of movement, which is then being responded to by the appropriate motion detectors[63,64,92]. Fourier transforms of reverse phi and phi motion show motion energy at opposite quadrants indicating the reversal of the direction of motion (Figure 1-7)[66].

Visual information, whether chromatic or achromatic, is carried by the two separate parallel pathways, the ON and OFF channels, from the retina to the visual cortex[109]. The ON channel responds to the light increments or positive contrasts through excitations, whereas it responds to light decrements or negative contrasts through inhibitions. On the contrary, the OFF channel responds to light decrements through excitations and vice versa. Some behavioral studies suggest that reverse phi motion, which is a stimulus that contains both contrast polarities, occurs as a result of interaction between ON and OFF cells at the early stage of motion processing[66,94]. However, there are other well-designed psychophysical studies that contradict this idea and conclude that the ON and OFF pathway do not converge until the early stage of motion perception[83,110]. There is neurophysiological evidence for the convergence of ON and OFF channels at the primary visual cortex that found an intact direction and orientation tuning of V1 neurons when ON channel was pharmacologically blocked[76].

If reverse phi motion is processed within the ON or OFF channels and there is no interaction between them, it would involve correlation between excitations and inhibitions. For example, if reverse phi motion is processed within the ON channel, the correlation between the excitation to the bright target and the inhibition to the dark target would result in a weaker motion response because of the differences in their amplitude and time course[80,111]. Therefore, it may result in a weaker sensitivity for reverse phi than a phi motion, which has same luminance contrast. In the study by Edwards and Badcock[110], the participants could not perceive an opposite direction of motion in a reverse phi random dot stimulus. In addition, the threshold number of signal dots required to report the global motion direction was higher for a reverse phi stimulus than for a stimulus that had only black dots or white dots, indicating lower sensitivity for reverse phi. Wehrahn and Rapf (1992) found that a larger temporal delay was required to respond correctly to the temporal order of a contrast reversed line pairs[83]. They also found that the threshold temporal delay for black line pairs was found to be higher than that of white line pairs and was low only for narrow spatial separations compared to white line pairs.

Moreover, the ON and OFF channels have intrinsic differences in their function which is correlated with their anatomy. The ON cells have a larger receptive field[80] and hence lower spatial resolution than OFF cells[112]. OFF cells have faster response dynamics than ON cells[113]. Visual evoked potentials to dark stimuli are larger than that of the bright stimuli[113]. Psychophysical evidence to the perceived differences in light increments and decrements reveal that light decrements are detected faster and have lower detection thresholds than light increments[81,82]. In the central retina, there are more OFF center cells than ON-center cells and their representation at the cortex predominates that of ON-cells. Using line pairs to assess the temporal order, Wehrhahn and Rapf[83] found that the threshold temporal delay for white line pairs was lower than that of black line pairs, concluding that the responses of OFF pathway is not equal to that of ON-pathway. Considering these differences in response dynamics of these two pathways, we predict reverse phi motion to have differences in the spatio-temporal characteristics and a weaker sensitivity than phi motion with no contrast reversals. However, earlier studies that looked at the spatio-temporal separation for perceiving coherent motion conclude that the two motion stimuli are processed by a common short-range mechanism[39,90,107]. Wehrhahn[114] and Bours et al.[107] found similar optimal spatio-temporal offsets values for reverse phi and phi motion. Bours et al.[107] also found that the sensitivity to reverse phi and phi motion are equal.

With inconsistent results in the literature on the processing of reverse phi motion, the purpose of this study was to measure the spatiotemporal limits and coherence thresholds of reverse phi using random dot kinematograms and see if it corresponds with or differs from that of phi motion. We found that the spatio-temporal characteristics were similar for reverse phi and phi motion for a small range of spatial-temporal offsets. The coherence threshold of reverse phi was higher than that of phi motion. Our findings suggest that both reverse phi and phi motion are processed through short-range mechanism. However, processing of the global motion with inverting contrast does not happen as effectively as that with the same-contrast.

2.3 Methods

The study was approved by the Institutional Review Board ORE # 22235. The stimuli were generated using Matlab 2016b Psychtoolbox package[114] (The MathWorks, Inc., Natick, Massachusetts, United States).

2.3.1 Subjects

Nine naïve and one experienced (MKP) human subjects participated in the study. All participants gave a written informed consent and all the procedures followed the tenets of Declaration of Helsinki. The study was approved by the institutional review board of University of Waterloo. The subjects aged between 18 and 35 years with a visual acuity of 6/9 or more and normal contrast sensitivity as measured by Freiburg test were included. Any subject with ocular or brain related disease and those who did not give consent were excluded from the study.

2.3.2 Experimental setup

The experiment was presented on a 19.5" Dell E2014H monitor (1600x900 pixels, 8 bits/pixel, 60Hz) with NVIDIA GeForce GT 640 graphics card. The monitor was gamma corrected. The luminance output of the monitor was measured using SpectraScan Model PR-670 (Photo Research Inc., Chatsworth, California). The participants viewed the screen binocularly from a viewing distance of 60cm in a dim room and used a keyboard to respond. Each pixel subtended 0.03° from this viewing distance.

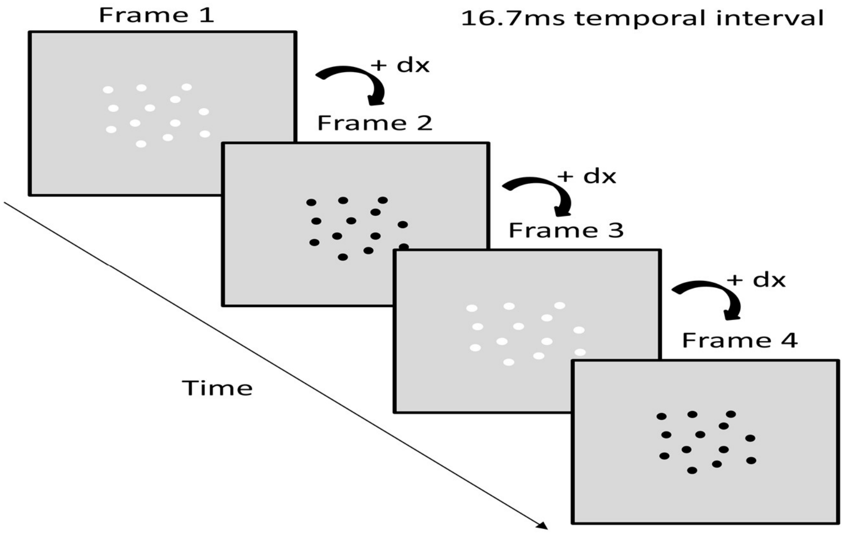
2.3.3 Stimuli

The stimulus used was a sparse random dot kinematogram (RDK) [115] with 500 dots presented in a central 10x10deg aperture. We used RDK because reverse phi depends on the brightness difference and not on the form[39], so any stimulus could be used, however, motion coherence can be best represented using RDK as the signal and the noise components can be represented by separate elements of the stimulus. In addition, random dots have been able to distinguish the short- and long-range motion systems well[44,101]. The lifetime of the dots was 2 frames (33.4ms), after which the dead dots were repositioned in a random spot within the aperture. Likewise, the dots leaving the aperture were repositioned at random locations at the other edge of the aperture. A limited dot lifetime was used to avoid unwanted correlations between same-contrast or opposite contrast dots. The size of the dots was 0.13° (7.8 arc min) in diameter because reverse phi is best seen in fine-grained patterns rather than large targets[39]. The dots had a luminance of 82 cd/m^2 for white and 0.3 cd/m^2 for black. The dot contrast was 99%. All the dots in a single frame were of similar contrast. The gray background had a luminance of 23 cd/m^2.

Two stimulus conditions were presented – phi and reverse phi motion – in separate runs. In phi motion, the dots remained white throughout the trial; whereas, in reverse phi, the contrast of the dots reversed upon each displacement, i.e., white dots changed to black, then back to white and so on in the successive frames.

2.3.3.1 Spatio-temporal limits

The dots were displaced by a spatial offset of 0.1 to 1.35 degrees in variable steps, which was achieved by varying the dot speed from 6 to 54.7 deg/sec, respectively. The temporal interval between two successive appearances of the dots was varied from 16.7ms to 66.8ms in the multiples of 16.7ms. For the temporal intervals greater than 16.7ms, the frames intervening the next appearance of the dots had blank grey. Figure 2-1 shows the presentation sequence of the reverse phi stimulus for a 16.7ms and 33.4ms temporal interval. The duration of the stimulus was 500 ms, so the number of frames presented was 30. Each combination of the spatial and temporal offset was repeated 10 times in a random order according to the method of constant stimuli. The dots moved in 100% coherence in one of the four directions; right, left, up or down. The subjects fixated at the central fixation cross and responded to the direction of motion (25% guess rate). No feedback was provided on the correctness of the response.



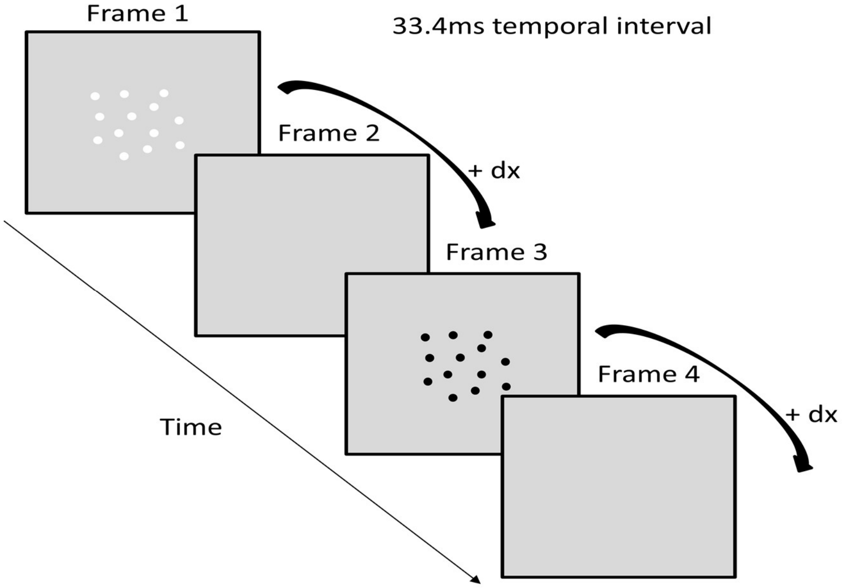


Figure 2-1 Presentation sequence of the first 4 frames of the reverse phi motion stimulus when the temporal interval was 16.7ms (top) and 33.4ms (bottom). The number of dots was 500 and the duration of the stimulus was 500ms.

2.3.3.2 Motion sensitivity experiment:

The dots were displaced by a spatial offset of 0.2 degrees resulting in a dot speed of 12.2 deg/sec. The temporal interval between two successive appearances of the dots was 16.7 ms. The spatial and temporal offsets were chosen based on the literature[66] and our preliminary results on spatiotemporal limits in which the hit rates were close to 100%. The duration of the stimulus was 500 ms, so the number of frames presented was 30. According to the coherence level, out of 500 dots, only a certain percentage of the dots moved in the same direction while the rest moved in random directions in any angle. The motion coherence level was varied from 0 to 100% in variable steps. For example, at 50% coherence level, 50% of the dots (250 dots) moved in a coherent direction, say, to the right, the rest of the dots (250 dots) moved in a random direction. Each coherence level was repeated 10 times in a random order according to the method of constant stimuli. The direction of motion could be in one of the four directions; right, left, up or down. The subjects fixated at the central fixation cross and responded to the direction of motion (25% guess rate). No feedback was provided on the correctness of the response.

2.3.4 Data Analysis

The correct response for the phi motion was the direction of physical movement of the dots. The correct response for the reverse phi motion was the opposite direction to the physical movement of the dots. The hit rates were calculated for each combination of spatial and temporal offsets and compared between phi and reverse phi motion. Dmax, the maximum spatial displacement that gave a coherent motion, is defined as displacement of the [0.6 (Cmax - 50) + 50]% correct point, where Cmax is the maximum correct score in that function of interest[73]. Repeated measures ANOVA and post hoc analysis were done to analyse the difference in the correct responses between reverse phi and phi motion. Psychometric function was plotted with the percentage of correct response against the motion coherence levels and a sigmoid function (1/(1+e^-((x-xo)/b))) was used to fit the data, where xo is the threshold, and b is the slope. The coherence threshold read off at 63% probability was compared between the phi motion and reverse phi motion using paired t test. The alpha error was set at 5% for the statistical significance.

2.4 Results

Ten subjects participated in the study. The mean age of the participants was 30±2years. We measured the spatial and temporal limits for reverse phi and phi motion by obtaining the direction of motion for various combinations of spatial and temporal offsets. We also measured the motion coherence threshold for an optimal spatial and temporal offset for both reverse phi and phi motion.

2.4.1 Spatio-temporal limits

Figure 2-2 shows the results of the experiment as percentage of correct responses for phi and reverse phi motion plotted against the spatial offsets for each temporal interval tested. We found that the plots for reverse phi and phi motion were similar only when the temporal interval was 16.7ms, particularly for smaller displacements. The difference between the two motion types became larger at higher spatial and temporal offsets.

At 16.7ms temporal interval, the percentage of correct responses increased as the spatial offset increased and reached 100% at 0.3deg spatial offset and then started declining after 0.5deg. The curves were similar for phi and reverse phi motion, however, reverse phi showed greater decline after 0.5deg compared to phi motion. Statistically, there was no main effect of motion type on the percentage correct (p=0.095), however, there was a significant main effect of spatial offset, $F(3.44,30.97) = 21.38$, $MSE = 811.36$, $p=<0.001$ and significant interaction between motion type and spatial offset, $F(2.88,25.93) =$

5.09, *MSE* = 855.93, *p*=0.007. The percentage correct response for reverse phi was significantly lower than phi motion for all spatial offsets >0.5deg (paired t test, p<0.05).

Similar trend was observed for the temporal interval of 33.3ms for phi motion, however, reverse phi showed greater reduction in the percentage of correct responses at all the spatial offsets with peak performance at 0.3deg and 0.4deg. Statistically, there was a significant main effect of motion type, *F*(1,9) = 60.19, *MSE* = 573.48, *p*<0.001, spatial offset, *F*(2.78,25.01) = 25.57, *MSE* = 1116.45, *p*<0.001, and no significant interaction between motion type and spatial offset, *p*>0.05. Except at 0.4 and 0.72deg spatial offset, the percentage correct response was statistically lower by a significant amount for reverse phi than phi motion (*p*<0.05)

At a temporal interval of 50.1ms, there was a clear distinction in the percentage of correct responses between phi and reverse phi motion with reverse phi showing only chance level responses. Statistically, there was a significant main effect of motion type, *F*(1,9) = 68.79, *MSE* = 1415.11, *p*<0.001 and no significant main effect of spatial offset and no interaction between them (*p*>0.05). There was a steady >70% correct response for phi motion at all the spatial offsets tested, which also declined significantly when the temporal interval was increased to 66.8ms. At higher temporal intervals, spatial offsets up to only 0.5deg were measured because of the chance level performance in the reverse phi motion.

The optimal spatial offset was 0.3-0.5deg (18-30 mins of arc) at which there was a 100% correct response for both reverse phi and phi motion. The optimal temporal offset was 16.7ms for reverse phi and 16.7-33.4ms for phi motion. The upper spatial displacement limit (Dmax) defined as the spatial offset at which the percentage of correct response was 80% was 0.55 deg (33 mins of arc) for reverse phi and 0.8 deg (48 mins of arc) for phi motion at 16.7ms temporal interval. At 33.4ms, Dmax was 0.45deg (27 min of arc) for reverse phi and 0.58 (34.8 mins of arc) for phi motion.

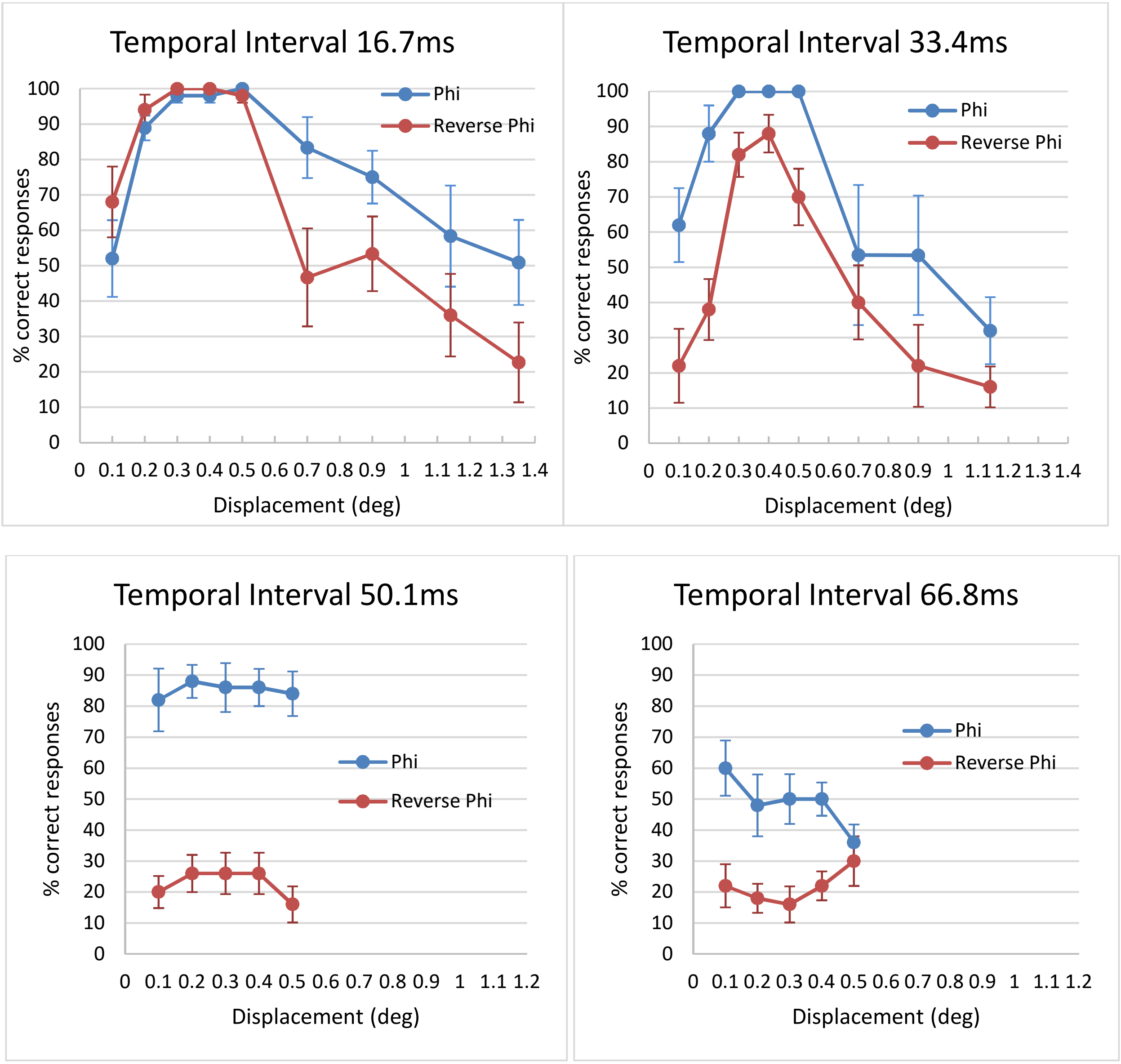


Figure 2-2 Percentage of correct responses (mean±SE) for phi and reverse phi motion as a function of displacement in visual angle for temporal intervals of a) 16.7ms, b) 33.4ms, c) 50.1ms, d) 66.8ms. The mean scores of 10 participants is shown.

The same data was visualized with the percentage of correct responses plotted against the temporal interval for the spatial offsets of 0.1, 0.2 and 0.3 deg, which showed clear differences between phi and reverse phi motion (Figure 2-3). At the spatial offset of 0.1 deg, the percentage of correct responses for phi motion increased as the temporal interval increased and declined at 66.8ms, which was not statistically significant. At the spatial offset of 0.2 deg and 0.3 deg, as the temporal interval increased, the percentage of correct responses for phi motion improved and remained stable around 85% and started declining at 66.8ms temporal interval. In contrast, reverse phi responses declined to chance level right at 33.4ms for 0.1 and 0.2 spatial offset, however, the performance improved for 33.4ms at 0.3 deg and higher spatial offsets.

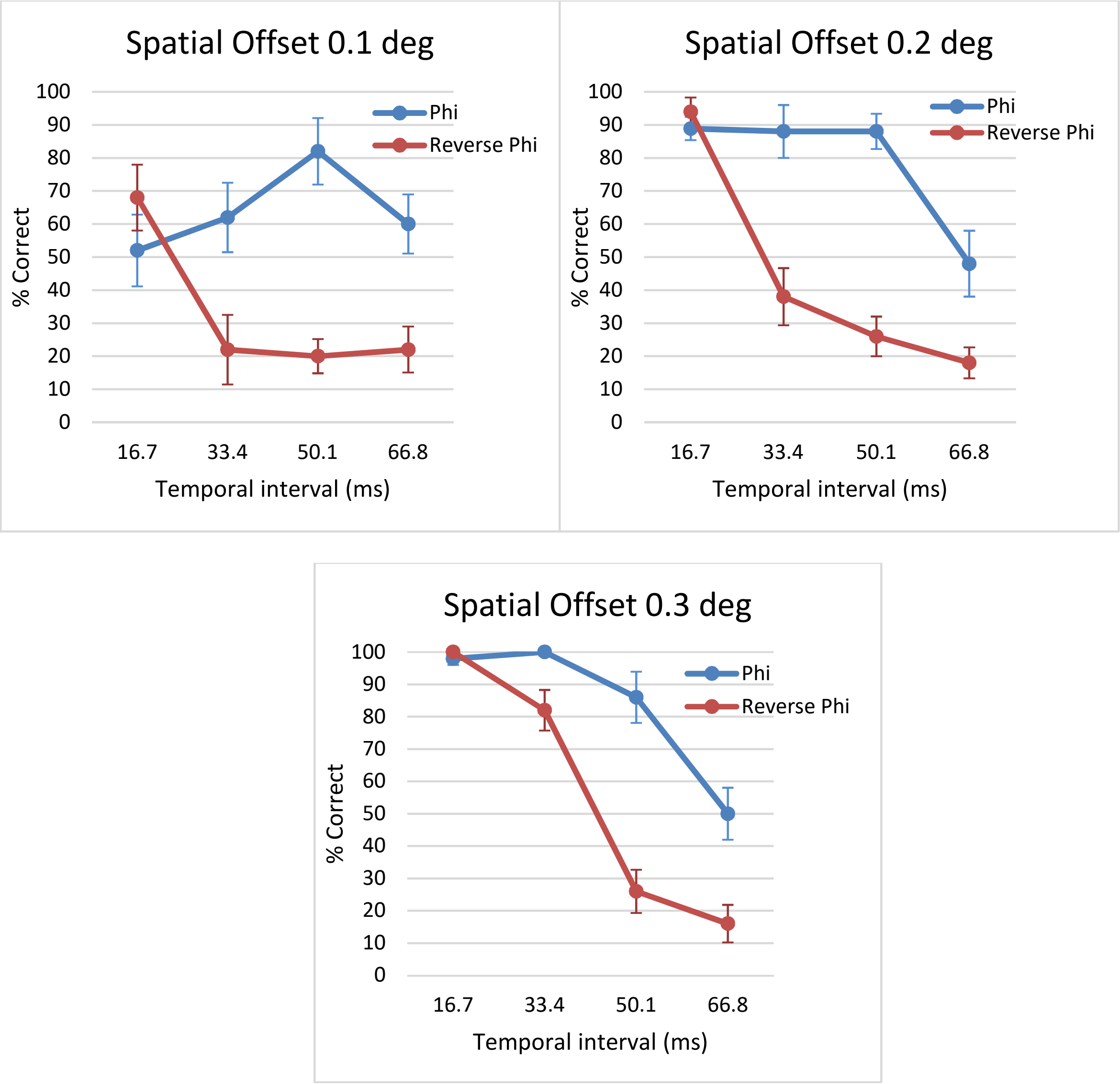


Figure 2-3 Percentage of correct responses (mean±SE) for phi and reverse phi motion as a function of temporal interval for spatial offset of a) 0.1deg, b) 0.2deg, c) 0.3deg.

2.4.2 Motion Sensitivity

Figure 2-4 shows the psychometric function plotted for the motion sensitivity of phi and reverse phi motion. The mean motion coherence threshold was 14.5±3.2% for phi motion and 25.9±6.7% for reverse phi motion. The motion coherence threshold of reverse phi was higher than that of phi motion and the difference was statistically significant (paired t test, p=.03).

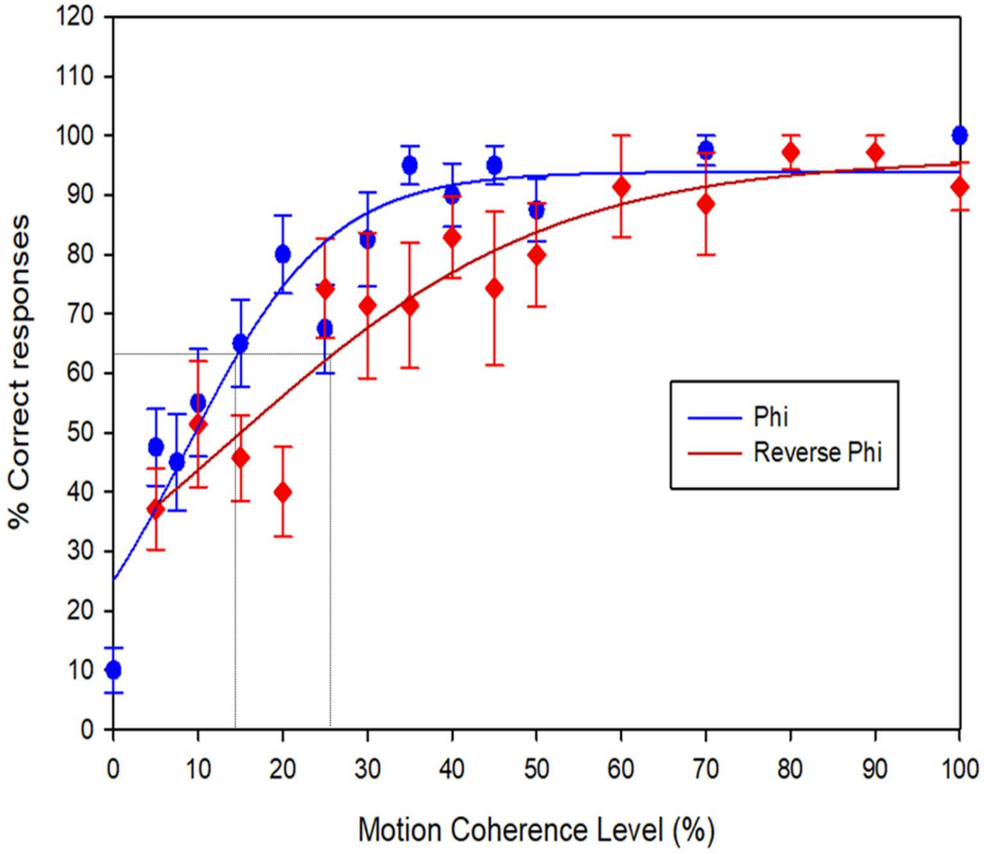


Figure 2-4 Psychometric function of motion sensitivity of phi and reverse phi motion. Mean of 10 participants is plotted and the error bars indicate standard error. Spatial offset of 0.2 deg and a temporal interval of 16.7ms used.

2.5 Discussion

We measured the spatio-temporal limits and the coherence threshold for reverse phi motion and compared it with that of the phi motion. The random dot kinematogram that we used had limited dot lifetime of 2 frames so that any correlation between similar contrasts in a reverse phi stimulus and any correlation between opposite contrasts in a phi motion stimulus could be avoided. We obtained the direction of motion responses for all combinations of spatial and temporal offsets that we used to find the optimal combination for both motion types and used those parameters to test the motion sensitivity.

Our experimental results showed that the percentage correct responses for reverse phi motion was similar to that of phi motion for a small range of spatial-temporal combinations, especially when the spatial displacement was smaller and the temporal interval was shorter. This suggests that both phi and reverse phi motion are processed through the same short-range mechanism. This conclusion conforms with that of previous studies[39,90,107,116]. Earlier studies that looked at the spatio-temporal separation for perceiving coherent motion found similar optimal spatio-temporal offsets values for reverse phi and phi motion and concluded that the two motion stimuli are processed by a common short-range mechanism[39,90,107,116]. However, the optimal spatial offset of 0.3-0.5deg that we reported for both phi and reverse phi was slightly higher than that reported in the previous study[66]. The short-range system is active when the spatial offset is about 15mins of arc and the temporal interval is <100ms[44]. However, when random dot kinematograms are used instead of a 2-frame stimulus, the spatial properties of the short-range system could be expanded to 10-20deg[117]. Bours et al.[107] reported an optimal spatial and temporal offset of 0.1deg and 25ms, respectively, at which the motion coherence threshold was the lowest. At their optimal spatial offset of 0.1deg, we found that the percentage of correct response for both reverse phi and phi motion was lower (about 70% or less).

Dmax is the upper displacement limit after which the motion system cannot solve the correspondence problem and hence, renders the stimulus incoherent. The Dmax, from Bours et al.[107] (2009) study was 36 mins of arc (0.6 deg) for both reverse phi and phi motion, which compared well with our results for reverse phi (0.55 deg or 33 mins of arc), but it was lower than that we found for phi motion (0.8 deg or 48 mins of arc). Dmax of a short-range motion is known to be affected by the field size of the stimulus with increased Dmax observed for an increased field size[118,101]. We used a 10x10deg stimulus aperture size while Bours et al.[107] used an 8x8deg aperture size. The 15mins of arc (0.25 deg) limit quoted for short range mechanism was from a field size covering 1.8deg of eccentricity[119]. It can be seen that the studies that used increased field size has reported higher Dmax values, particularly for phi motion[118,101]. The effect of field size on the Dmax of reverse phi has a potential for future studies.

The optimal temporal interval of 16.7ms that we found was constrained by the refresh rate of the monitor that we used. For phi motion, the optimal temporal interval ranged from 16.7ms-33.4ms, which was greater than that reported by Bours et al.[107]. The difference between the two studies in the optimal spatial temporal characteristics could have been due to the task performed. In our study, the subjects had to report the direction of motion in a 100% coherent motion, whereas in their study, the participants had to do the same for a variable coherent motion, which involves both integration and segregation. Our result indirectly corroborate the findings of Nishida[73] who reported a maximum ISI of <30ms for the discrimination of RDK. Considering the design of our stimulus, at temporal intervals greater than 16.7ms, there was an ISI between the frames that contained the dots, for example, 16.7ms ISI for 33.4ms temporal interval, 33.4ms ISI for 50.1ms temporal interval, and so on. The performance of reverse phi dropped to chance level at an ISI of 33.4ms and above whereas phi motion maintained around 80-90% correct response for an ISI of 33.4ms. This suggests that the spatial parameter of ISI affects reverse phi more than the phi motion. In addition, it has been noted that luminance defined regular square wave grating with an ISI of <40ms results in a reversed perception of motion and at longer ISI, it results in veridical motion[120]. We did not observe a reversed direction for our phi stimulus.

Although the percentage correct responses for phi and reverse phi motion overlapped to some extent for a small range of spatio-temporal intervals, the performance was lower for reverse phi motion at larger spatial displacements and larger temporal intervals, which was consistent with the previous studies[55,39,90,107,116]. Reverse phi declined faster than phi motion at larger spatial and temporal offsets. This was in accordance with the explanation of reverse phi by Anstis[39], where he suggests that the opposite direction of reverse phi is perceived because of the correlation between the nearest points of similar brightness in the successive frames. Reverse phi breaks down soon after the points move far apart at larger spatial displacements to be correlated together. This suggests that at larger displacements and longer temporal intervals, the motion processing is taken over by a different mechanism – the long-range mechanism. There is evidence for interaction between short-range/first-order and long-range/second-order mechanism at the low-level motion detection[55]. For reverse phi stimulus, the effects of these two mechanisms are opposite. When reverse phi is processed through short range mechanism, it gives a reversed perception of motion direction. However, when it is processed through the long-range mechanism, it gives a forward direction of motion in the same direction as the physical displacement. Therefore, as the spatial and temporal offsets are increased, the influence of long-range mechanism increases for reverse phi motion resulting in a lower performance than phi motion.

The differences in the performance seen between the two motion types, especially at higher temporal intervals and higher spatial displacements may also suggest that there is an inefficiency in processing bright (positive contrast) and dark (negative contrast) in contrast to same contrast polarity at these combinations of spatial and temporal offsets. In the visual system, light increments or positive contrasts are processed by the ON pathway, whereas the light decrements or negative contrasts are processed by the OFF pathway. Within the ON pathway, the neurons respond to bright spots by excitations and dark spots by inhibitions. The correlation between excitations and inhibitions would result in weaker responses compared to correlations between both excitations (same contrast) because excitation and inhibition responses within the same channel vary in amplitude and response dynamics, especially when the stimulus is of high contrast[80,111] and low dot density[107]. The alternate plausible explanation could be that this inefficiency is due to the processing of both contrasts within the same channel. Many studies support this idea of independent processing and no combination of ON and OFF channels in the low-level motion detection[83,121,122]. In the study by Edwards and Badcock[121], the participants could not perceive an opposite direction of motion when a reverse phi random dot stimulus was presented at the fovea, therefore, the authors concluded that the ON and OFF channels remain segregated until before the global motion processing. However, electrophysiological recording in cats from the simple cells of V1 region reveal that the reverse phi stimulus consisting of opposite contrast polarity can be effectively processed within the same neural pathway, for instance, ON or OFF pathway[123]. These neurons have excitatory center and inhibitory borders. For example, in the ON pathway, a left-ward tuned neuron would respond to a bright object moving to the left in the same way as it would respond to a bright object in the excitatory center moving to the right in addition to changing its contrast to black at the inhibitory zone, which causes more excitation. There is a possibility that the ON-center and the OFF-center neurons could have different spatio-temporal tuning compared to that of the ON-center and OFF center neurons combined. On the other hand, it could be that the motion information from the ON and OFF pathways combine together only for a narrow range of spatial and temporal intervals beyond which they don't function efficiently, thus, resulting in lower percentages of direction reversals. In fact, there are differences in the response dynamics of the ON- and OFF- center neurons with positive contrast being processed slower than the negative contrast[80,124]. These processing delays could have amplified the differences between the motion types at higher temporal intervals.

The motion sensitivity in terms of coherence threshold was higher for reverse phi motion than phi motion. Our results are supported by a few studies[55,110]. Edwards and Nishida[55] found that a larger number of signal dots were required to perceive reverse phi motion than phi motion at higher speeds, which was obtained by either increasing the spatial separation or decreasing the temporal interval. Edwards and Badcock[110] found that the threshold number of signal dots required to report the global motion direction was higher for a reverse phi stimulus than for a stimulus that had only black dots or white dots. The differences in the response timings of ON and OFF channels could explain the lower sensitivity for reverse phi motion. However, Bours et al.[66] found that the sensitivity to reverse phi and phi motion are equal, although their data show that reverse phi has a relatively higher threshold than the phi motion that is not significant. The tuning curves of MT neurons to reverse phi stimulus was found to be lower in amplitude and broader in half-height tuning width than a phi stimulus, which means that the reverse phi elicits a weaker and a less directionally selective response compared to phi motion[96]. Oluk et al.[108] observed that the proportion of correct responses for reverse phi was approximately 5% less than that of phi. These results suggest that reverse phi is a weaker stimulus compared to phi motion.

The obvious reason for the discrepancy between our results and the previous studies is in the motion stimulus used and the extent of the second-order component in it. Similar to the recent study by Bours et al.[107], we used a sequential random dot motion stimulus with only a low degree of second order motion mechanisms contributing to the results. In contrast, a two-frame motion stimulus may have a greater contribution of second-order mechanism, resulting in a forward motion or reduced occurrence of reversed perception of motion direction. As discussed earlier, the more the contributions of second-order mechanism in the processing of reverse phi motion, the less will be its sensitivity. This is because of its preponderance at slow speeds and larger displacements, which do not work well for reverse phi motion.

The limitation of the study is in the design of the reverse phi stimulus at higher temporal intervals. The inter-stimulus interval between the presentations of the dots within a trial could have triggered the influence of second-order or the long-range motion system. This interference is known to affect the perception of reversed direction of motion[55]. Instead of the ISI, presenting the preceding frame twice would have avoided the excessive flicker in the stimulus and at the same time presented the desired temporal interval.

To conclude, our results suggest that the performance of motion direction discrimination for reverse phi and regular phi was similar for a small range of spatio-temporal offsets, suggesting a common short-range mechanism. However, the performance at larger displacements and temporal intervals, and the motion sensitivity was lower for reverse phi motion which could be due to the relative contribution of long-range mechanism and the differential response dynamics of ON and OFF channels.

Chapter 3

Effect of Eccentricity on Spatio-temporal tuning and Sensitivity of Reverse Phi Motion

3.1 Overview

3.1.1 Background

When the contrast of a moving pattern is reversed in the successive frames, then the perceived direction of motion is reversed. This phenomenon called reverse phi is believed to occur due to the interaction between the ON and OFF pathways and is processed by the short-range mechanism. Due to the anatomical and physiological differences between the central and peripheral retina, the perception of reverse phi, its spatio-temporal characteristics and motion sensitivity were tested at the central and peripheral presentations of the stimulus and was compared with the phi motion

3.1.2 Methods

We measured the spatial and temporal characteristics of phi and reverse phi motion and their coherence thresholds in 10 participants using random dot kinematograms presented to the fovea and the superior retina at 15deg eccentricity. The dot size was 0.13° for central stimulus, which was scaled up to 0.26° for peripheral presentations. The temporal intervals tested varied from 16.7ms to 50.1ms in the steps of 16.7ms. The spatial displacements tested ranged from 0.1 to 1.35 degrees. For motion coherence thresholds, the signal dots were varied from 0 to 100% with different step sizes for phi and reverse phi motion. Subjects reported the direction of motion.

3.1.3 Results

Reverse phi was observed both in central and peripheral presentations. There was no difference in the percentage correct responses between central and peripheral presentations for phi and reverse phi, except at 0.1 and 0.4 deg spatial offsets at 33.4ms temporal interval where reverse phi was perceived better at the periphery at 0.1 deg and at the center at 0.4deg. In terms of motion sensitivity, there was no difference in the motion coherence threshold between central and peripheral presentations for either phi or reverse phi motion.

3.1.4 Conclusion

Although there are anatomical and physiological differences between the center and periphery, the motion signals of reverse phi are processed equally well at the fovea and the retinal eccentricity tested.

3.1.5 Keywords

Reverse Phi, spatial temporal, motion sensitivity, eccentricity, motion coherence, apparent motion, phi motion

3.2 Introduction

Visual perception starts with the formation of an image of the surrounding world on the retina. The way in which this image is processed further depends on whether the image falls on the central retina or the peripheral one because of their anatomical and physiological differences. Anatomically, the central retina is populated by a greater number of cone photoreceptors and midget ganglion cells, whereas the peripheral retina is concentrated with rod photoreceptors and parasol cells, which greatly differ in their morphology and receptive fields. The central retina has one-to-one connections between the nuclear layers whereas at the peripheral retina, there is more convergence of information via many-to-one connections. There are various degrees of disproportionate representation of the visual field at various levels of visual processing. At the lateral geniculate nucleus and primary visual areas, there is over-representation of inputs from central visual field than the peripheral one. However, the feedback projections from the extra-striate non-visual areas to the primary visual cortex focus on the neurons representing the periphery visual field than the central one[125]. Due to the differences in the central and peripheral visual systems, the spatial resolution and the temporal modulation are different. The central visual system has low temporal resolution and high spatial resolution while the peripheral visual system has high temporal resolution and low spatial resolution and is specialized for motion detection.

The perception of motion direction requires correlation of spatio-temporal changes of the object. There are differences in this processing observed between the central and peripheral presentation of the stimulus. With regard to speed changes, central presentation of acceleration had lower detection thresholds than deceleration, whereas with peripheral presentation around 5-15deg, the effect is reversed[126]. Electrophysiological studies on macaque monkeys suggest that the spatio-temporal range for directional interactions at MT and V1 correlates with retinal eccentricity[23]. The maximum spatial interval that was reported for MT was 1.8°(0.2-6) and for V1 was 0.59° (0.2-1.28). The maximum temporal interval was not different between MT (91ms) and V1 (114ms). The maximum spatial displacement limit (Dmax) to perceive a coherent motion, increased with increasing eccentricity[127].

Reverse phi is an apparent motion phenomenon where the perceived direction of motion is reversed due to the object reversing its contrast in every presentation of its trajectory. This motion stimulus, which consists of both light increments and decrements, requires correlation between the ON and OFF channels. Considering the overall anatomical differences between central and peripheral retina and its connections, we wanted to investigate if the responses for reverse phi motion are different for central and peripheral presentations. Earlier studies show that the perception of reverse phi varies with retinal eccentricity[39,55,121]. A reversed direction of motion was observed both in the peripheral vision and foveal vision, especially when the stimulus was a fine-grained pattern[39]. However, for a large isolated target, reverse phi was seen only when it was presented at the periphery. For a given spatial displacement, larger grains or larger size of dots gave a larger apparent displacement than smaller sized dots[39]. This suggests that the perception of reverse phi largely depended on the stimulus and its size. In addition, since reverse phi motion is processed by short-range mechanism[39,128], the presentation of the stimulus at different eccentricity should affect its perception. A few studies have found that reverse phi was not observed at the central presentation[55,121],[129]. However, when it was presented at the periphery, reverse phi direction was reported[54].

We wanted to see if there was any difference in the spatio-temporal characteristics and motion sensitivity between the central and peripheral presentations of reverse phi and phi motion. Also, we wanted to investigate the differences between reverse phi and phi motion for the peripheral presentations. Additionally, we scaled up the dot size to compensate for the peripheral resolution, and hence could compare the responses for phi and reverse phi motion with and without size scaling.

3.3 Methods

The study was approved by the Institutional Review Board ORE # 22235. The stimuli were generated using Matlab 2016b Psychtoolbox package[114] (The MathWorks, Inc., Natick, Massachusetts, United States).

3.3.1 Subjects

Nine naïve and one experienced (MKP) human subjects participated in the study. All participants gave a written informed consent and all the procedures followed the tenets of Declaration of Helsinki. The study was approved by the institutional review board of University of Waterloo. The subjects aged between 18 and 35 years with a visual acuity of 6/9 or more and normal contrast sensitivity as measured by Freiburg test were included. Any subject with ocular or brain related disease and those who did not give consent were excluded from the study.

3.3.2 Experimental setup

The experiment was presented on a 19.5” Dell E2014H monitor (1600x900 pixels, 8 bits/pixel, 60Hz) with NVIDIA GeForce GT 640 graphics card. The monitor was gamma corrected. The luminance output of the monitor was measured using SpectraScan Model PR-670 (Photo Research Inc., Chatsworth, California). The participants viewed the screen binocularly from a viewing distance of 60cm in a dim room and used a keyboard to respond. Each pixel subtended 0.03° from this viewing distance.

3.3.3 Stimuli

The stimulus and the psychophysical paradigm used in this study was the same as those described in the previous chapter. In this study, the spatio-temporal characteristics and the motion sensitivity was measured both at the center and the periphery. For peripheral presentation, the stimulus was presented 10 degrees inferior to the fixation cross, which was presented at the top of the monitor; therefore the center of the stimulus aperture was 15 degrees below the fixation cross (**Error! Reference source not found.**). The monitor was oriented vertically to fulfill the presentation requirements. The subjects’ fixation was monitored by the experimenter throughout the experiment. The size of the dots was 0.13° (7.8 arc min) in diameter for central presentations. It was scaled up to 0.27° (16.2 arc min) for the peripheral presentation. This was based on the formula for human cortical linear magnification factor, M_{linear} = A/(E+e2), where A is the cortical scaling factor in mm, E is the eccentricity in deg at which the stimulus is presented, and e2 is the eccentricity in degree at which the stimulus subtends half the cortical distance that it would subtend at fovea[130,131]. For V1, A is taken as 29.2mm and e2 as 3.67°[132,131]. By multiplying the dot size at fovea and M_{linear}, we got 0.27° as the dot size for 10 deg eccentricity. The number of dots was reduced to 450 dots, which should not have an effect on the perception of reverse phi or phi motion because lowering the dot density does not lower the sensitivity to reverse phi or phi motion[107,118]. The experiments were conducted both with and without scaling of the dot size. Each trial was repeated randomly for 10 times according to the method of constant stimuli. The dots moved in 100% coherence in one of the four directions – right, left, up and down (25% guess rate). The subjects responded to the direction of motion of the dots. No error feedback was provided. In the motion sensitivity experiment, a spatial offset of 0.2°

and a temporal interval of 16.7ms were used at the periphery. The coherence level varied from 0 to 100% in variable steps. The subjects responded to the global motion direction.

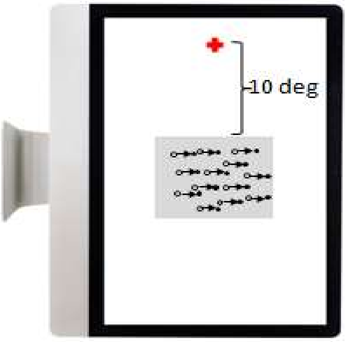


Figure 3-1 Stimulus presentation at the periphery

3.3.4 Data Analysis

Correct response for the phi motion was the direction of physical displacement whereas for reverse phi, it was the direction opposite to the physical displacement. For the spatio-temporal limits, the hit rates were calculated for each stimulus condition and compared between central and peripheral presentations using repeated measures ANOVA and post hoc analysis. For motion sensitivity comparisons, the psychometric function was plotted with the percentage of correct response against the motion coherence levels and the thresholds at 63% probability were compared between central and peripheral presentation conditions using paired t test. A sigmoid function (1/(1+e^-((x-xo)/b))) was used to fit the data, where xo is the threshold, and b is the slope. The alpha error was set at 5% for the statistical significance.

3.4 Results

3.4.1 Phi motion – Center versus Periphery

3.4.1.1 Spatial-temporal characteristics

Figure 3-2 shows the percentage of correct responses as a function of spatial displacements for different temporal intervals. At the temporal intervals of 16.7ms and 33.4ms, the percentage of correct responses increased as the displacement of the dots increased and slowly decreased after 0.5deg for both center and periphery ($p<0.05$). However, at 50.1ms of temporal interval, the responses flattened out around 70-80% for all spatial displacements at both center and periphery. Comparing the direction of motion responses for phi motion between center and periphery, we found no statistical difference in the percentage of correct responses for any temporal intervals and spatial offsets (*p*>0.05). Since the responses for both center and periphery were similar, the upper spatial displacement limit (Dmax) defined as the spatial offset at which the percentage of correct response was 80% was also similar and not significantly different between center and periphery.

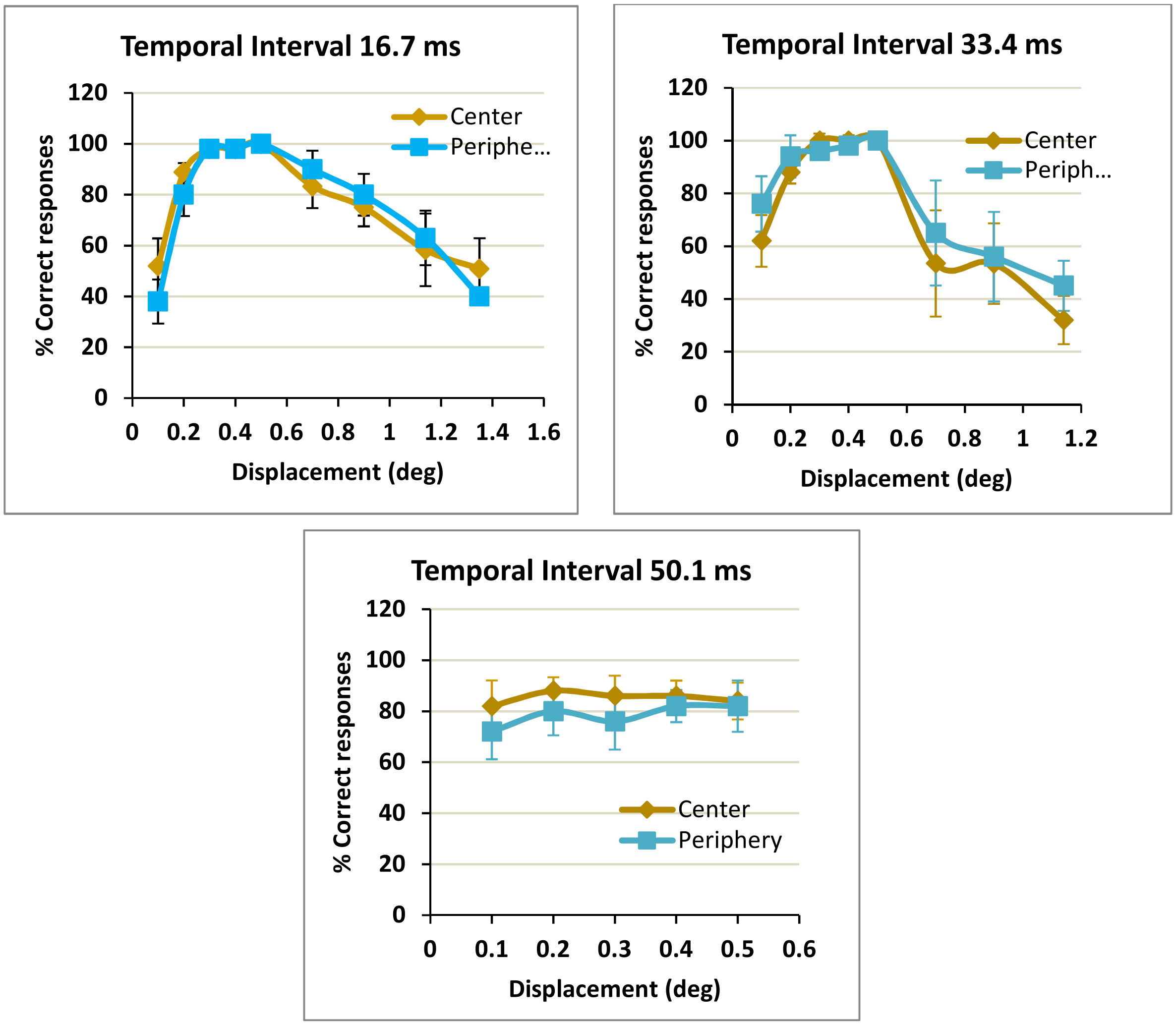


Figure 3-2 Percentage of correct responses (mean±SEM) for phi motion as a function of displacement between center and peripheral presentations (scaled up for size) for temporal intervals of a) 16.7ms, b) 33.4ms, c) 50.1ms.

3.4.1.2 Motion sensitivity

Figure 3-3 shows the psychometric functions of phi motion sensitivity for central and peripheral presentations. The mean motion coherence thresholds for phi motion at the central and peripheral presentations were 14.5±3.2% and 16.28±6.02%, respectively and the difference was not statistically significant (paired t test, *p*=.136).

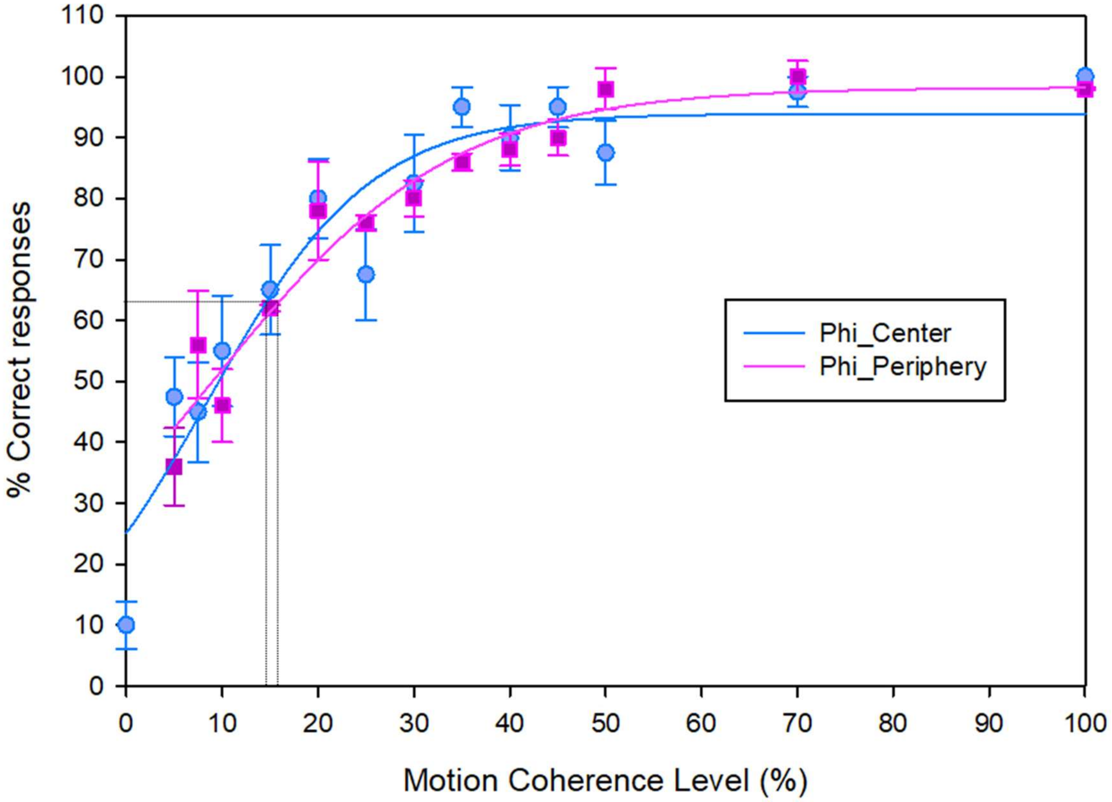
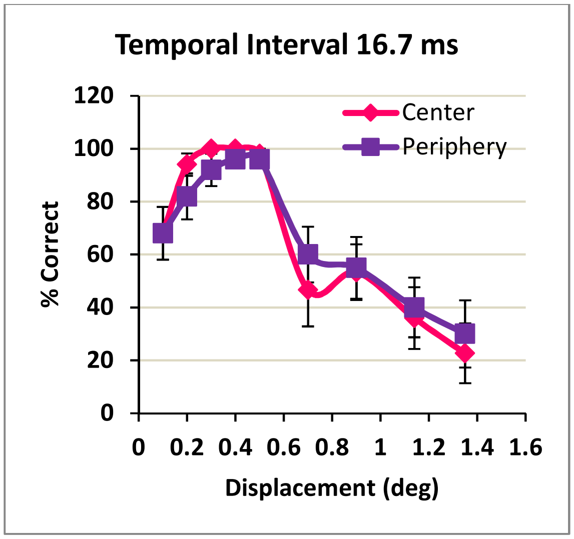


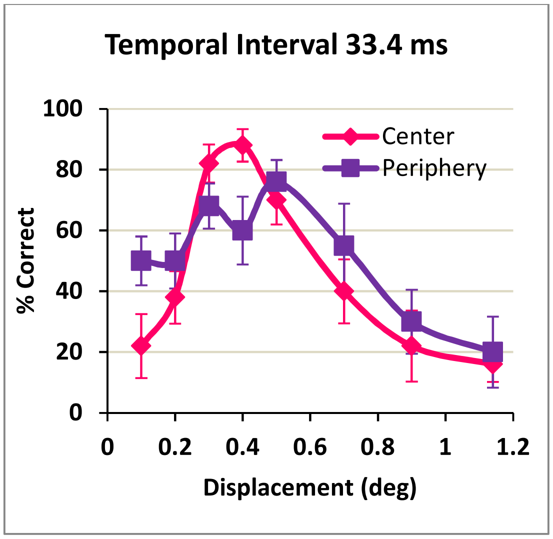
Figure 3-3 Psychometric function of motion sensitivity for phi motion at central and peripheral presentations. Mean of 10 participants is plotted and the error bars indicate standard error.

3.4.2 Reverse Phi – Center versus Periphery

3.4.2.1 Spatial-temporal characteristics

The participants perceived a reversed direction of motion at both central and peripheral presentations of reverse phi motion. Figure 3-4 shows a similar graph as Figure 3-3 but for reverse phi motion. It shows the percentage correct responses as a function of displacement for different temporal intervals. Similar to phi motion, at the temporal interval of 16.7ms, the percentage correct response increased as the displacement increased and then decreased at 0.5° for both center and periphery. The slight decrease in the performance at periphery at 0.3° and 0.4° spatial displacements was not statistically significant. But for 33.4ms temporal interval, the responses at the center and periphery differed at 0.1 deg (*p*=.025) and 0.4 deg (*p*=.029) spatial displacements. At 0.4 deg, the correct responses at the center were greater than those in the periphery. On the contrary, at 0.1°, the correct responses at the periphery were greater than the central ones, which had only chance level performance. This suggests that reverse phi is better seen at the periphery only for smaller displacements when the temporal interval is 33.4 ms. However, the mean responses did not reach >80% in any of the spatial offsets at the peripheral presentation. Similar to 16.7ms temporal interval, the mean responses decreased after 0.5°. At 50.1ms, the responses were at chance level for both center and periphery at all the spatial displacements and there was no statistical difference between central and peripheral performance. Since the responses for both center and periphery were similar, the upper spatial displacement limit (Dmax) defined as the spatial offset at which the percentage of correct response was 80% was also similar and not significantly different between center and periphery.





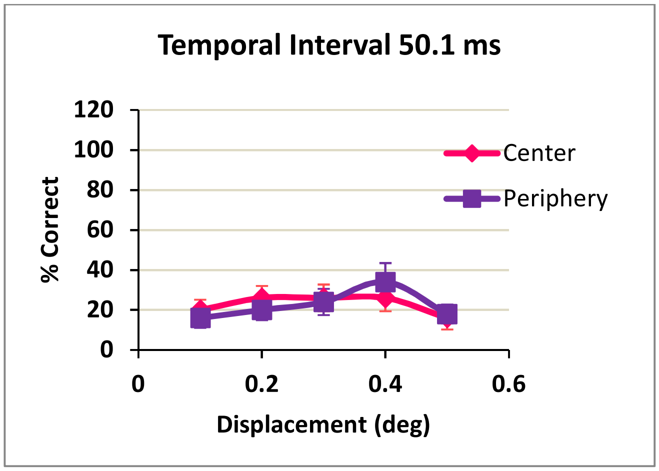


Figure 3-4 Percentage of correct responses (mean±SEM) for reverse phi motion as a function of displacement between center and peripheral presentations for temporal intervals of a) 16.7ms, b) 33.4ms, c) 50.1ms.

3.4.2.2 Motion sensitivity

Figure 3-5 shows the psychometric functions of motion sensitivity for reverse phi stimulus at central and peripheral presentations. For reverse phi motion, the coherence threshold was 25.9±6.7% and 40.62±6.28% at the center and periphery, respectively (*p*=.057). The coherence threshold for reverse phi motion was higher at the periphery; however, due to the variability of the data, the difference was not statistically significant.

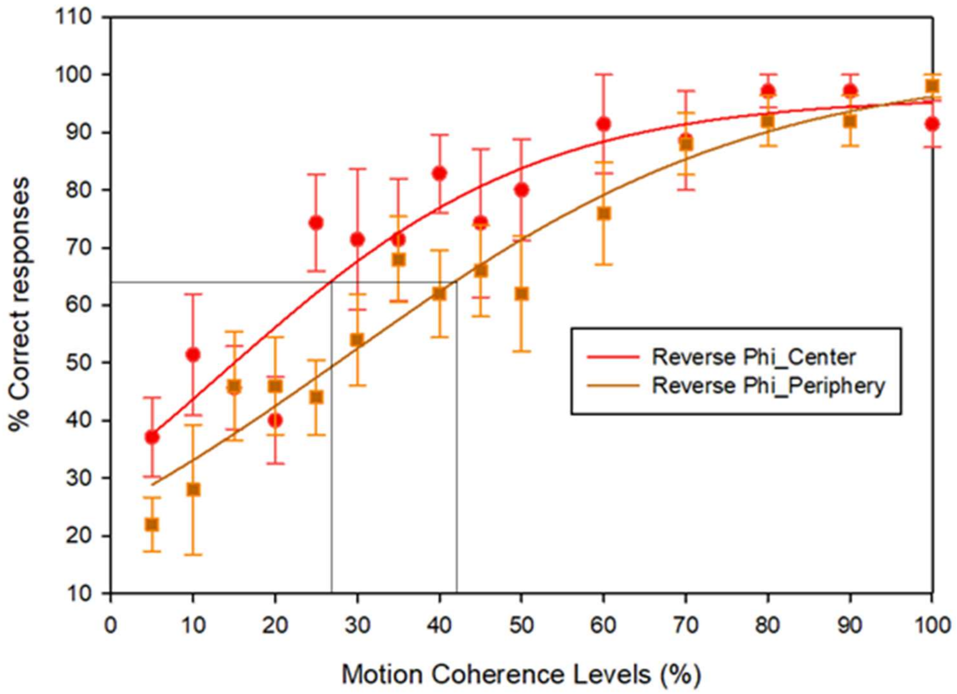


Figure 3-5 Psychometric function of motion sensitivity for reverse phi motion at central and peripheral presentations. Mean of 10 participants is plotted and the error bars indicate standard error.

3.4.3 Phi versus Reverse Phi at Periphery

3.4.3.1 Spatial-temporal characteristics

When the spatio-temporal characteristics of phi and reverse phi motion were compared at the periphery, we found that the difference in the percentage of correct responses was statistically significant at the spatial displacements of 0.1deg, 0.7° and 0.9° at the temporal interval of 16.7 ms (*p*=.034) (Figure 3-6). At 33.4 ms and 50.1 ms of temporal offsets, the responses decreased for reverse phi motion at all the spatial displacements except at 0.7° of 33.4 ms temporal interval (Figure 3-6) and these differences between reverse phi and phi motion were statistically significant (*p*<.001).

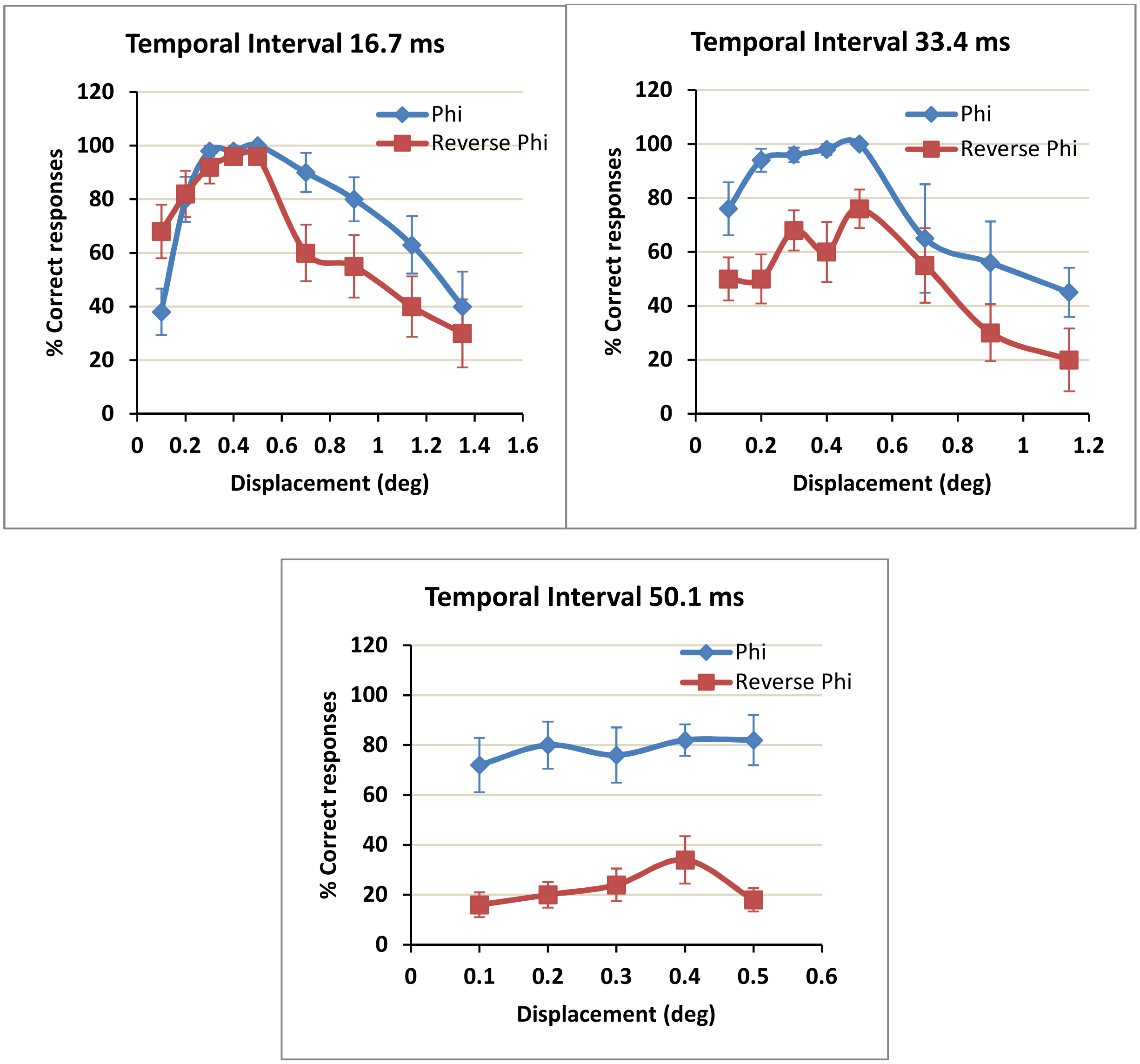


Figure 3-6 Percentage of correct responses (mean±SEM) for phi and reverse phi motion at periphery as a function of displacement for temporal intervals of a) 16.7ms, b) 33.4ms, c) 50.1ms.

3.4.3.2 Motion sensitivity

When the peripheral motion coherence thresholds were compared between the phi and the reverse phi motion, reverse phi had higher thresholds (40.62±6.28%) compared to phi (16.28±6.02%), which was statistically significant (*p*=.004) (Figure 3-7).

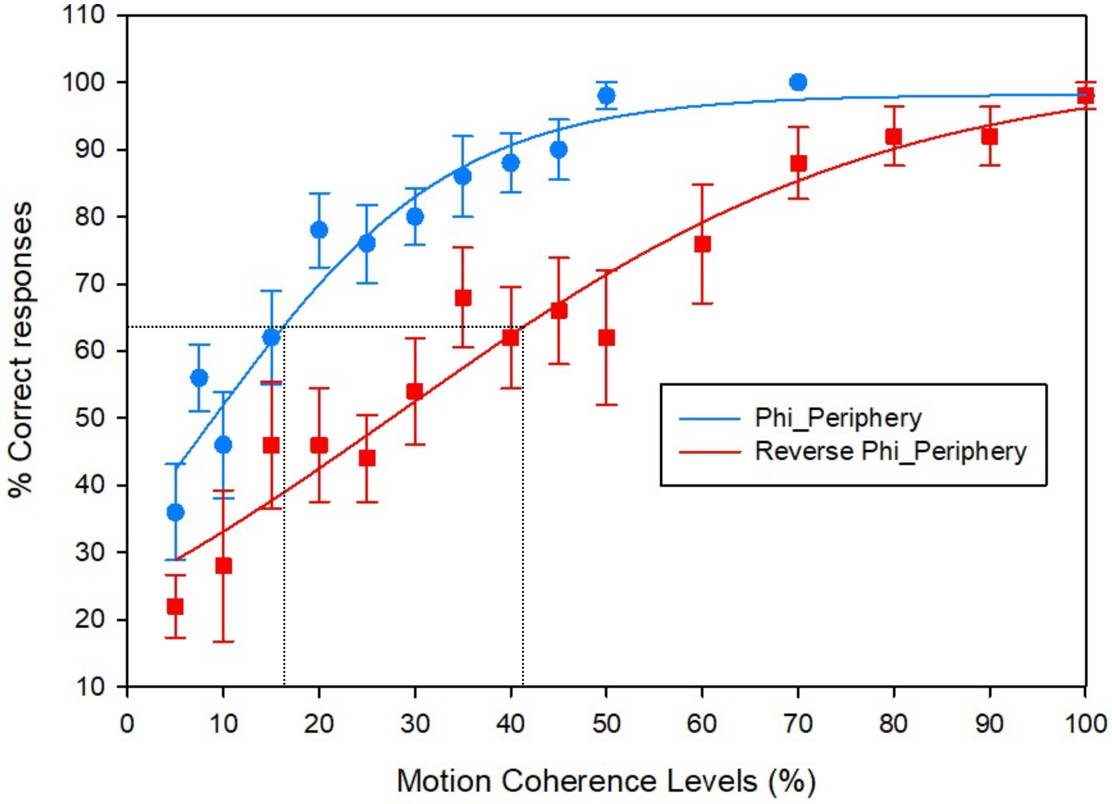


Figure 3-7 Psychometric functions of motion sensitivity for phi and reverse phi motion at peripheral presentations. Mean of 10 participants is plotted and the error bars indicate standard error.

3.4.4 With and without scaling – Phi motion

We wanted to see if there was any difference in the percentage correct responses when the dot size was not scaled for the peripheral presentations (Figure 3-8). We found that when the dot size was not scaled, the percentage of correct responses was significantly lower at all spatial offsets except 0.1 deg at 16.7ms temporal interval ($p<.05$). Also, at the temporal interval of 33.4 ms, the percentage correct responses were lower without scaling, but the difference was not statistically significant for all spatial offsets ($p>0.05$) except for 0.5 deg ($p=.029$). At 50.1 ms temporal interval, the responses were similar with and without scaling.

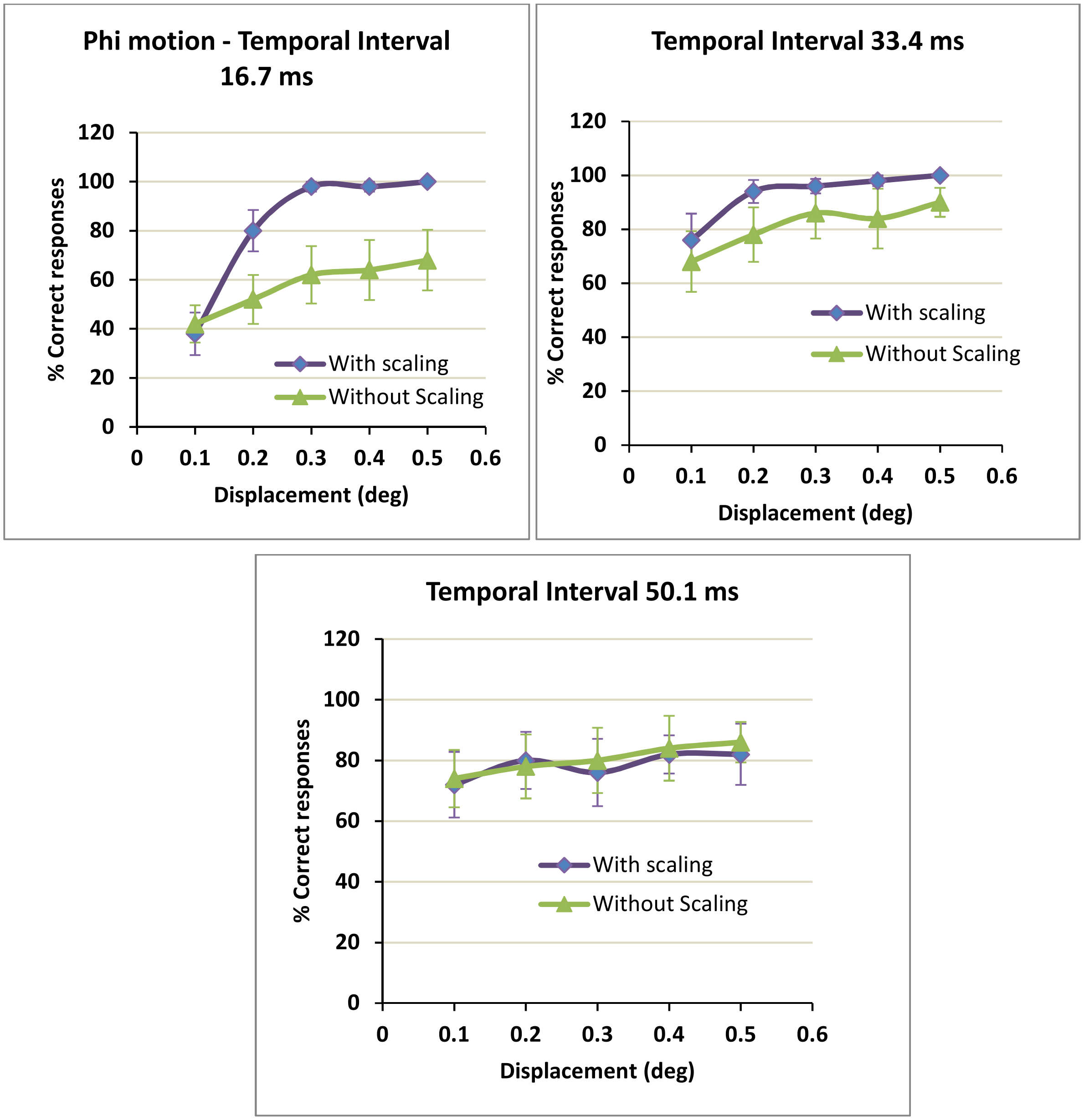


Figure 3-8 Percentage of correct responses (mean±SEM) for phi motion at the periphery with and without scaling for dot size as a function of displacement for temporal intervals of a) 16.7ms, b) 33.4ms, c) 50.1ms.

3.4.5 With and without scaling – Reverse Phi motion

For reverse phi motion, the percentage correct responses with size scaling were lower than without scaling at the temporal interval of 16.7 ms and 33.4 ms but the difference was statistically significant only at 0.4 deg spatial offset at 33.4 ms temporal interval (*p*=.033) (Figure 3-9). Similar to phi motion, there was no difference between with and without scaled data at 50.1 ms temporal interval.

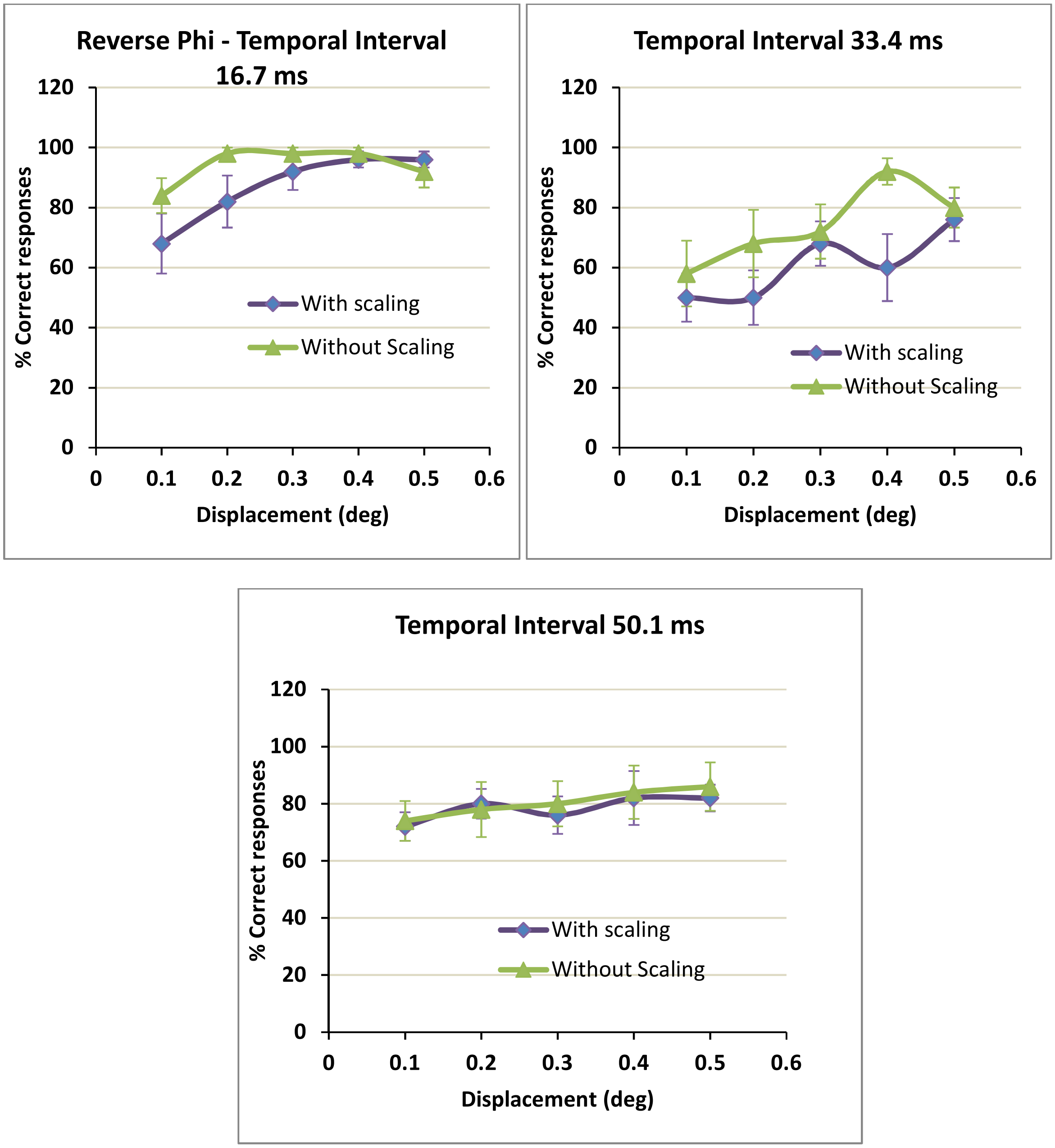


Figure 3-9 Percentage of correct responses (mean±SEM) for reverse phi motion at the periphery with and without scaling for dot size as a function of displacement for temporal intervals of a) 16.7ms, b) 33.4ms, c) 50.1ms.

3.5 Discussion

In this study, we investigated whether the responses for reverse phi and phi motion were different for central and peripheral presentations. We found that the responses were similar at both central and peripheral presentations for phi motion and reverse phi motion for most of the combinations of spatial and temporal offsets, except at 0.1 and 0.4 deg spatial offsets at 33.4 ms temporal interval. In terms of motion sensitivity, there was no difference in the motion coherence threshold between central and peripheral presentations for both phi and reverse phi motion.

For reverse phi motion stimulus, our participants reported seeing a reversed direction of motion both at the center and periphery for a range of spatial and temporal separations, which was consistent with previous studies[39,128,106]. Anstis and Rogers[106] noted that the reverse phi was not observed when the spatial displacement was >10' (0.17 deg) at the foveal presentation and <20' (0.33 deg) and >30' (0.5 deg) for peripheral presentations. They also reported that the temporal interval was not a matter of concern in observing reverse phi. In our study, we found that the reverse phi was seen up to 0.5 deg (100% response), i.e., 30' both at the center and periphery. The differences found in the spatial characteristics between the studies could be due to the stimulus used and the eccentricity tested. Anstis and Rogers[106] used a single dot 2-frame interval stimulus whereas our stimulus was a random-dot kinematogram presented for 500 ms. We presented our stimulus at 15 degrees eccentricity but the earlier paper does not mention the peripheral stimulus location.

Our results showing similar spatio-temporal characteristics for both central and peripheral presentations of reverse phi and phi motion contradicts with some of the previous results. When reverse phi stimulus is processed by a first order motion unit, a reversed direction of motion is observed, on the other hand, when the same stimulus is processed by a second-order motion unit, which involves full-wave rectification, a forward motion is observed[49,55,71]. Increasing the eccentricity is a way of decreasing the degree to which reverse phi motion drives the second-order motion units[133–135], which should result in higher probability and strength (lower thresholds on global motion coherence) of reverse phi perception at the periphery. In other words, with increasing eccentricity, the relative strength of first order signal increases to a point where it dominates the second-order system[49,55,71,70]. Studies have reported that the reverse phi was stronger at the periphery than at the center[55,70,106,129], just like the ordinary phi motion[36,136]. Mather et al.[70] observed that the reversed direction was observed at an eccentricity of 5 deg for all displacements used in the study, while at the center, reversed direction was seen only for smaller displacements and forward motion was seen for larger displacements. This suggested that the short-range or first order motion system as opposed to second-order motion was active in the periphery. Edwards and

Nishida[55] tested the perception of reverse phi motion at 0, 10, 15 and 20 deg eccentricity and found an increase in reverse phi perception from fovea to the periphery. A few studies reported an absence of reverse phi perception or a forward motion when the contrast-inverting stimuli were presented at the fovea[55,72,129]. These results from the literature differ from our findings. We found that the responses were similar at the periphery and the center for reverse phi motion, except at 33.4ms when the spatial separations were 0.1 deg (6') and 0.4 deg (24'). At 0.1 deg, the peripheral responses were stronger than the central ones, while at 0.4deg, the central responses were stronger than the peripheral ones. A possible reason for the invariance in the performance between the center and the periphery could be the size-scaling. Many visual functions show peripheral invariance if the stimulus parameters took into account the cortical magnification factor[137,138].

Dmax increases rapidly with retinal eccentricity[119,118]. However, due to the similar spatio-temporal characteristics at center and periphery, we found that the Dmax values were also similar between the center and periphery. Possible reason for such discrepancy could be the scaling up of the stimulus size at the periphery. In our study, we scaled up the stimulus size by increasing the size of dots and keeping the stimulus area constant, while in other studies the stimulus area was increased keeping the dot size constant. This could have eliminated the impact of eccentricity on Dmax[118]. Moreover, there are reports indicating that variations in dot size up to 10-15 arc min does not alter Dmax very much[139,140].

In addition, the motion sensitivity in terms of motion coherence threshold was similar between center and periphery for both phi and reverse phi motion, although there was a statistically insignificant increase in the reverse phi motion threshold at the periphery. Edwards and Nishida[55] found a marginal decrease in the number of signal dots required for reverse phi perception with increasing eccentricities. In contrast, they found that phi motion perception was constant across different eccentricities and the fovea, which supports our results on phi motion. This indicates that the mechanism for processing phi motion remains unaltered in the periphery.

When reverse phi and phi motion was compared at the periphery, the differences found in the spatio-temporal characteristics and the motion sensitivity at the central presentation was seen at the periphery too. Edwards and Nishida[55] have shown that the threshold number of dots that signal phi motion and reverse phi motion were comparable at higher eccentricities of 20 deg. But we found that at an eccentricity of 15 deg, the coherence threshold was higher for reverse phi than phi motion. Perhaps, if we had tested at further eccentricities, the sensitivities might have become similar.

In the peripheral task, the stimulus was scaled up in dot size to compensate for the relatively poor spatial resolution at the periphery. This compensation improved the performance for phi motion for shorter temporal interval and larger displacements. However, for reverse phi motion, size scaling decreased or maintained the performance compared to the results without scaling. Anstis[39] observed that a large sized stimulus gave a larger apparent displacement than a smaller sized target, according to which the performance should have been higher for size-scaled stimulus.

We conclude that increasing the eccentricity did not affect the spatio-temporal characteristics and motion sensitivity of phi motion, suggesting that the mechanism involving the short-range motion is unaffected with eccentricity, which could be due to the dot size scaling. Reverse phi motion sensitivity increases slightly at the periphery compared to center. The differences seen in these parameters between phi and reverse phi motion was maintained or even widened at the periphery.

Chapter 4

Transparent Motion in Reverse Phi

4.1 Overview

4.1.1 Background

When the contrast of successive frames is reversed in an apparent motion stimulus, the perceived direction is reversed. This is believed to be due to the inhibition of neurons tuned to the direction of physical displacement. In this study, we tested the inhibition hypothesis using transparent motion stimuli.

4.1.2 Methods

In the motion transparency experiment, two random dot kinematograms moved in the opposite directions at 100% coherence. The subjects had to report the direction of motion whether it was in the right diagonal or left diagonal direction. In the motion nulling experiment, phi and reverse phi motion moved in the opposite directions with a fixed number of reverse phi dots and a varying number of phi dots. The subjects had to report the motion direction whether the dots moved in the left, right or in both directions.

4.1.3 Results

Subjects confirmed perceiving a reversed direction for a reverse phi stimulus using single RDK. In motion transparency experiment, subjects reported perceiving motion along the direction of stimulus displacement for both motion conditions. In the motion nulling experiment, reverse phi motion was dominated by a much smaller phi motion signal.

4.1.4 Conclusion

In reverse phi motion, transparency motion was perceived rather than an orthogonal motion. This suggests two possible conclusions: 1) there is no inhibition caused by a reverse phi motion on neurons tuned to the direction of physical displacement suggesting that reverse phi follows evidence-only hypothesis at the low-level motion detectors, 2) if any inhibition was present, it was insufficient to elicit an orthogonal motion. The results of nulling experiment suggest that reverse phi is a weaker stimulus in the presence of regular phi motion.

4.1.5 Keywords

Transparent motion, inhibition, excitation, reverse phi, apparent motion, nulling

4.2 Introduction

When the contrast of a moving pattern is reversed successively, the direction of motion is perceived opposite to the physical displacement of the pattern. This phenomenon is known as reverse phi[39]. The motion system correlates the patterns of different contrast to give rise to the direction reversal. The reason why the reversal of perceived direction happens has been pointed to the shift in the balance of the motion energy to the opposite direction, which is then responded by an appropriate motion detector[64,65,92]. Therefore, the direction reversal was considered as a stimulus characteristic rather than a unique neural mechanism. A recent study showed that this direction reversal cannot be disregarded as merely a stimulus property, and it has a neural underpinning for the motion detection because reverse phi stimulus is made up of dark and white regions which can be carried by different channels of the visual system[141].

Contrast increments and decrements are processed by two separate neural channels constituting ON-center and OFF-center cells, which remain separate from bipolar layer of the retina till V1[76]. The processing of motion information from a reverse phi stimulus consists of correlations between contrast increments and decrements, which requires the two channels to combine the information at its first synapse at V1. It is believed that the direction reversal happens at V1 where the low-level motion detectors are present[95]. According to Mo-Koch model, the correlations between two opposite contrasts lead to excitatory signals in the detectors tuned to the direction opposite to the displacement, which was named as evidence model by Duijnhouwer and Krekelberg[96]. However, since motion detectors are opponently arranged, Bours et al.[95] proposed that the same effect can be elicited by having inhibitory signals to the neurons tuned in the same direction as the physical displacement, which was named as counter-evidence model. Whether there is excitatory response in one neuron or inhibitory response in the opponent neuron, the perceived direction for a reverse phi motion is in the opposite direction of the physical displacement. However, excitatory and inhibitory responses are regarded differently in the low-level neurons.

Excitations are narrowly tuned while inhibitions are broadly tuned to direction of motion[142]. This idea was proposed to explain the segregation of two motion vectors and integration of their motion aftereffects (MAE), especially when the two motion vectors are opposing each other. Adaptation to two orthogonal motion vectors, one in right diagonal and the other in left diagonal, caused broad unidirectional after-effects in the direction opposite to the vector sum of the adapting motion vectors[143,144]. Adaptation to an opposing transparent motion resulted in a bivectorial motion after effect in the directions orthogonal to the direction of the inducing vectors[142]. Transparent motion is a motion stimulus that has two motion components in the same part of the visual field[145] and the visual motion is capable of responding to multi-vectorial motion, which has more than one motion direction and/or speeds. Physiological studies have found that the primary visual cortex V1 cannot differentiate transparent motion from a single motion vector and that the perception of motion transparency is due to the activity of MT region[145,146]. Perception of orthogonal after-effect to a transparent motion was thought to be due to the weighted summation of the component vectors[147,148].

Based on the orthogonal motion after effects for transparent motion adaptation, reverse phi motion was compared to MAE, which is the result of inhibition of the fatigued neuron causing excitations in the opponent neuron. Bours et al.[95] proposed that if reverse phi motion was due to the inhibitory responses, then it should behave like MAE and these investigators found that a transparent reverse phi motion gave rise to an orthogonal motion and not a transparent motion along the stimulus presentation. Edward and Badcock[55] suggested that there must be inhibitions at the low-level motion detectors where the local motion is detected. However, we found that our participants did not observe orthogonal motion irrespective of the dot density, dot lifetime and spatial offset, but instead, they reported transparent motion.

4.3 Methods

The study was approved by the Institutional Review Board ORE # 22235. The stimuli were generated using Matlab 2016b Psychtoolbox package[114] (The MathWorks, Inc., Natick, Massachusetts, United States).

4.3.1 Subjects

Nine naïve and one experienced (MKP) human subjects participated in the study. All participants gave a written informed consent and all the procedures followed the tenets of Declaration of Helsinki. The study was approved by the institutional review board of University of Waterloo. The subjects aged between 18 and 35 years with a visual acuity of 6/9 or more and normal contrast sensitivity as measured by Freiburg test were included. Any subject with ocular or brain related disease and those who did not give consent were excluded from the study.

4.3.2 Experimental setup

The experiment was presented on a 19.5" Dell E2014H monitor (1600x900 pixels, 8 bits/pixel, 60Hz) with NVIDIA GeForce GT 640 graphics card. The monitor was gamma corrected. The luminance output of the monitor was measured using SpectraScan Model PR-670 (Photo Research Inc., Chatsworth, California). The participants viewed the screen binocularly from a viewing distance of 60cm in a dim room and used a keyboard to respond. Each pixel subtended 0.03° from this viewing distance.

4.3.3 Stimuli

Transparent motion stimuli consisted of two random dot kinematograms moving in opposite directions with 100% coherence, resulting in a percept of two sets of dots moving in opposite directions. Two types of motion stimuli were used: phi and reverse phi. The only difference between the two stimuli was alternating contrast polarity in reverse phi stimulus. Otherwise, both stimulus looked identical.

We varied the number of dots from 500 to 2500 (50% black) in a 10x10deg aperture. The lifetime of the dots was either 2 frames (33.4ms) or 3 frames (50.1ms), after which the dead dots were repositioned in a random spot within the aperture. Likewise, the dots leaving the aperture were repositioned at random locations at the other edge of the aperture. The size of the dots was 0.13° in diameter. The dots had a luminance of 82 cd/m^2 when white and 0.3 cd/m^2 when black. The gray background had a luminance of 23 cd/m^2. The dot contrast was 99%. The temporal interval was 16.7ms, and the spatial offset was either 0.2 or 0.3 deg. Stimulus duration was 1s. The number of dots and spatial offset were varied to conform to the stimulus parameters of the previous study[95] and to increase the chances of inhibition if at all any existed.

4.3.3.1 Experiment 1: Motion transparency

In the first part of the experiment, transparent motion stimulus was presented moving along the left diagonal or the right diagonal directions (Figure 4-1). Both components of the transparent motion could be either reverse phi or phi motion. Subjects responded to the direction of motion in a 2-alternative forced choice paradigm (right or left diagonal). From the literature, the expected perception in the phi motion condition was transparent motion along the stimulus movement, and orthogonal direction in the reverse phi condition because of inhibition of the neurons tuned to the stimulus directions, for e.g. perceiving up-down direction for a stimulus moving right-left. In this experiment, if the stimulus was moving in left diagonal and if the subjects see transparent motion, then they would report left diagonal, while if they see an orthogonal motion, then they would report right diagonal. Each trial was repeated 10 times in random order according to the method of constant stimuli.

In the second part of the experiment, two motion signals were run at diagonals to give rise to plaid motion. If reverse phi was due to inhibitions, subjects would report the plaid direction as opposite to the vector sum of the two diagonal motion signals. This experiment was done for both phi and reverse phi motion.

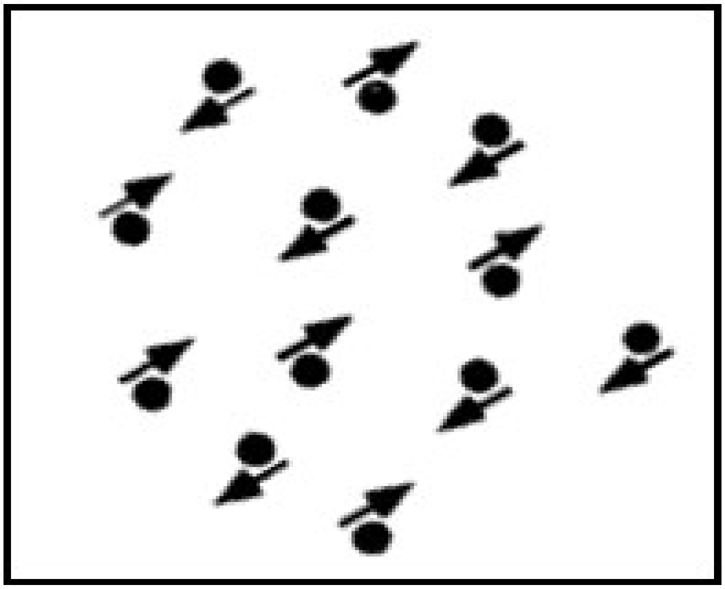


Figure 4-1 Transparent motion stimulus

4.3.3.2 Experiment 2: Nulling experiment

The aim of this experiment was to see whether reverse phi motion and phi motion gets cancelled if their percepts were in opposite directions. According to Bours et al.[107], reverse phi caused inhibitions in the neurons tuned in the same direction as the displacement. Therefore, a phi motion in the opposite direction to the reverse phi percept that causes excitations would cancel/ nullify the motion. On the other hand, if reverse phi causes excitations in the neurons tuned in the opposite direction of displacement, then adding a phi motion in the opposite direction of the reverse phi percept would elicit a transparent motion. To test this out, both phi and reverse phi motion were presented in the same direction physically either in the left or right-ward direction. There were 250 dots carrying the reverse phi motion signal and the number of dots carrying the phi motion signal was varied from 0 to 100% relative to the reverse phi motion signal in variable steps. Subjects responded whether the direction of motion was right, left or both (transparent motion) (33.3% guess rate). Each trial was repeated 10 times in random order according to the method of constant stimuli.

4.3.4 Data Analysis

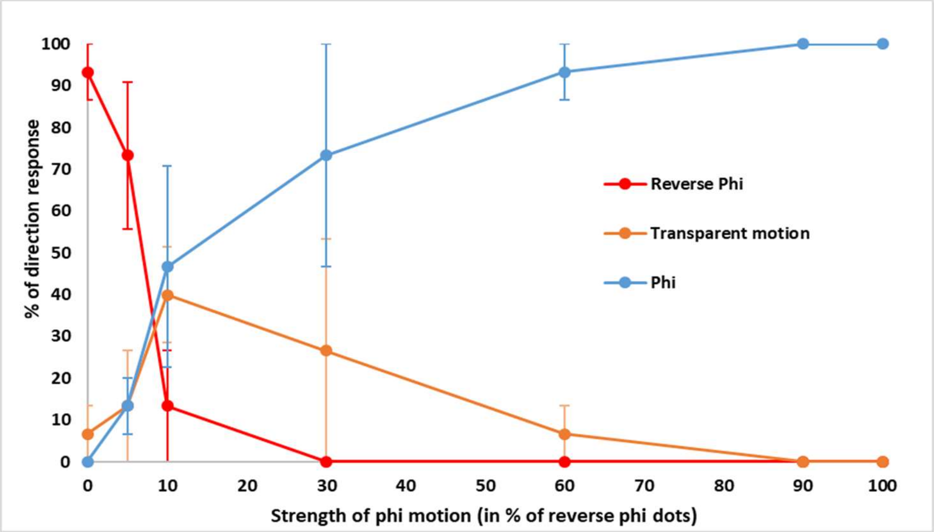
Hit rates of the motion direction were calculated for the phi and reverse phi motion. In the nulling experiment, the percentage of the direction of motion response was calculated for each strength of phi motion signal. The alpha error was set at 5% for the statistical significance.

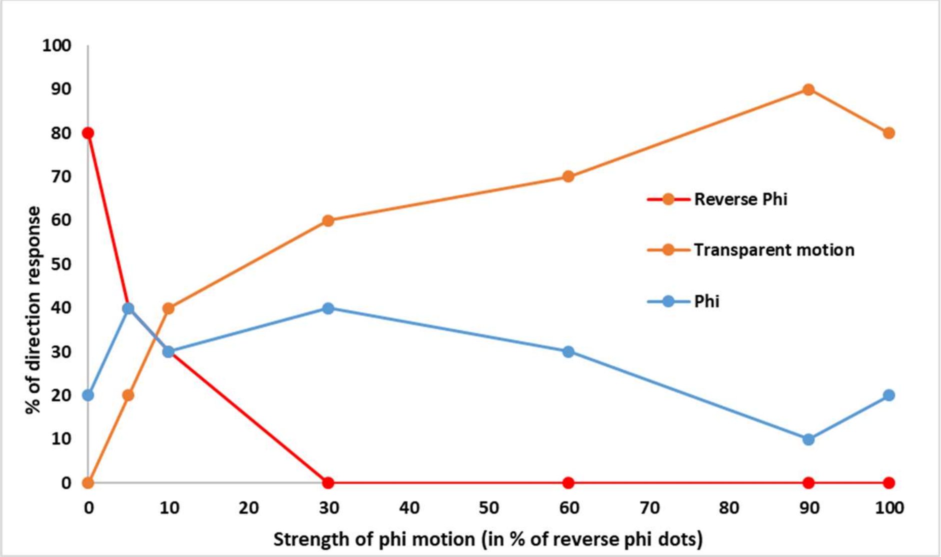
4.4 Results

Ten subjects participated in the study. The mean age was 30±2years. We investigated if orthogonal motion was observed in transparent reverse phi motion. We conducted two experiments – transparent motion and nulling experiments – to understand the mechanism of direction reversal in reverse phi motion. In the transparent motion experiment with phi motion components, two planes of dots moving in the opposite direction transparently were seen in all the trials. When the two opposing motions were of reverse phi signals, the subjects reported perceiving motion transparency, i.e., along the direction of the opposing vectors, rather than the orthogonal direction, on 97.5±2.5% of trials. This result was obtained with increasing spatial offsets, dot lifetime and dot density although the subjects reported difficulty in judging the motion direction at higher dot density. In the plaid experiment, the participants reported seeing plaid motion in the direction of the vector sum of the individual components of the stimulus about 96.4±3.8% rather than in the opposite direction.

In the nulling experiment, as the number of dots that carried phi motion signal increased, the percentage of times that they will see reverse phi motion will decrease. The percentage of trials in which the participants saw reverse phi motion reduced steeply and reached zero when the dots carrying phi motion was 30% (75 dots) of that with reverse phi signal. The percentage of trials in which motion transparency and phi motion was seen increased at the same rate till the stimulus had 10% (25 dots) of phi motion dots. There was increased variability in the responses between phi and transparent motion until the dots carrying the phi signal were 30% of the reverse phi signal. However, as the phi signal carrying dots increased further, the participants reported the direction of motion along the phi motion signal rather than transparent motion suggesting that the phi motion was stronger than the reverse phi that it was suppressed/ nullified. In contrast, one participant (MKP) reported motion transparency more than the phi motion (Figure 4-2). Similar to the average data, reverse phi perception decreased to zero at 30% phi signal, however, the perception of transparent motion and phi motion was flipped. The interesting thing to note was that this participant saw a phi motion in 20% of the trials when there were dots carrying only reverse phi signal, which suggests either that there was some same-contrast correlations present in the stimulus or that the participant pressed the wrong key a couple of times.

We were interested to know how the results would be if we forced the participants to choose only 2 options: phi or reverse phi motion. When we did the experiment on participant MKP, the result was similar to the experiment that had 3 options and the crossing point was at 10% phi signal dots.





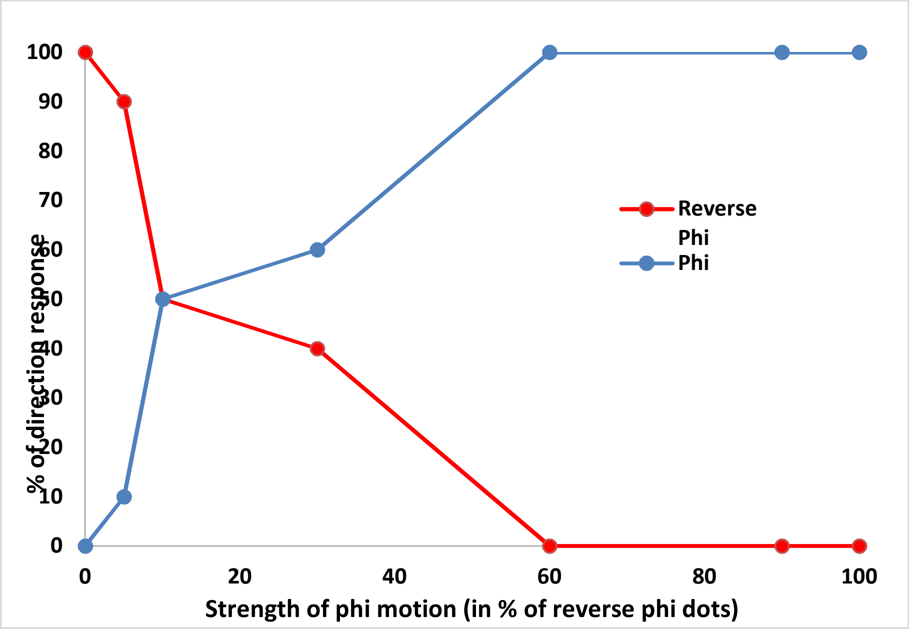


Figure 4-2 Results of Nulling experiment plotting % of direction of motion response (mean±SE) as a function of the strength of phi motion expressed in percentage of dots for A) all participants excluding MKP participant, B) MKP participant C) MKP participant with 2-way forced choice paradigm (right/left)

4.5 Discussion

In this study, we tested the reproducibility of the experiments by Bours et al.[95] on the mechanism of direction reversal of reverse phi. They observed an orthogonal motion direction when presenting a transparent motion with its components carrying reverse phi signal. They proposed that if reverse phi is due to inhibitory responses, the neurons tuned in the same direction as the component motion vectors will be inhibited, and the orthogonal directions will be disinhibited, resulting in a motion percept perpendicular to the actual movement. However, our participants did not report an orthogonal percept for a reverse phi transparent motion, which differs from their results. Reverse phi motion is believed to be perceived due to the correlations between opposite-contrasts, which are carried by the excitations of ON- and OFF– center cells. Such correlations, according to the model proposed by Mo-Koch[94], causes excitations in the neurons tuned to the direction opposite to the physical displacement of the object, i.e., in the percept direction. Bours et al.[95] proposed an alternative explanation to the same perceptual response, i.e., inhibitory signals in the neurons tuned to the stimulus direction. We used random-dot kinematograms with a limited lifetime of 2 frames similar to that used in previous studies[95,107]. From our previous experiments, we used an optimal spatio-temporal offset of 0.2/0.3 degrees and 16.7 ms, respectively, which is only barely different from that used in Bours et al study (0.1 degrees and 25 ms). At 0.1 degrees of spatial separation that they had used, we found that reverse phi was observed only for 70 odd percentages of trials. Therefore, it was prudent to use the spatio-temporal separations that resulted in a near 100% response of reverse phi.

Our results suggest that perception of motion transparency is possible with reverse phi motion. Even in the plaid experiment, we saw the perceived motion direction was the average of the component vectors and not in the direction opposite to it. These findings contradict the observations of Bours et al.[95]. It is possible that our stimulus, despite being similar to that used by Bours et al.[95], did not cause sufficient inhibition to elicit an orthogonal motion. When there is an inadequate amount of inhibition, it translates to inadequate amount of disinhibition. Due to the observation of orthogonal direction to a transparent motion of reverse phi, Bours et al.[95] compared the mechanisms of reverse phi with that of the MAE. MAE occurs due to the disinhibition of neuron population tuned in the directions opposite to the adapting motion. When bivectorial directions were presented, the direction of the aftereffect depended on the amount of adaptation (inhibition) to the individual motion vectors[147]. Therefore, if the amount of inhibition is less, the strength of the after-effect would be weaker or nil and as a matter of fact, the motion signals in a bivectorial MAE are very weak[149], which could be the reason why we did not observe the orthogonal direction. On the other hand, it is possible that the reverse phi caused excitations - in congruence with Mo-Koch model[94] - of the neurons tuned in the opposite direction to displacement of individual motion vectors instead of inhibitions that led to a perception of transparent motion along the direction of presentation.

Electrophysiological studies in the middle temporal region (MT) of macaque monkeys, which is a neural substrate for motion analysis, have shown that the motion percept and the activity in MT correlate with each other and that the reverse phi motion causes activation of neurons tuned to the direction opposite to the physical displacement[92,1]. In addition, the transparent motion in the opposite directions has no effect on motion energy in the orthogonal directions, as reported by Bours et al.[95], which should result in a motion percept not along the orthogonal direction.

The idea of reverse phi behaving as MAE was conceived from the observation of orthogonal MAE following adaptations to a transparent motion stimulus. When adapting to a transparent motion with opposite motion vectors, the ensuing MAE was in the orthogonal direction, suggesting that the integration of motion signals happens not just within neurons tuned to opposite directions (ratio model of MAE[150]), but within all the neurons tuned in all possible directions (distribution-shift model of

MAE[143])[142,151]. However, the motion system carries out both segregation of transparent motion during adaptation and integration of motion vectors after adaptation efficiently. This is possible only when assuming that the excitatory signals during adaptation are narrowly tuned and inhibitory signals during disinhibition are broadly tuned[142]. Moreover, the orthogonal MAE seen after adaptation to transparent motion was observed only when the test stimulus was dynamic and not static[142,143,147]. Dynamic MAE, if induced by a first order motion stimulus of high temporal frequency, is processed at the low-level motion detectors[152]. Verstraten et al. [147] suggests that the adaptation process that produces the MAE takes place at the level or beyond the motion integration site.

Bours et al.[95] observed that the orthogonal vectors of phi motion – one moving up and right and the other moving up and left - were seen as transparent motion and remained segregated. However, we observed a motion direction in the direction pointing to the average of the individual motion vectors. It is a known fact that such orthogonal motion vectors produce a plaid motion in a grating. This was indicated in a model simulation where presentation of closely related motion vectors, unlike the opposing motion vectors, produced unimodal distribution of activity with its peak at the middle of the two contributing vectors, which should give rise to a percept of upward motion rather than a transparent motion[151]. We are not sure why the participants in Bours study did not observe a motion vector at the average direction for phi motion.

In the nulling experiment, both reverse phi and phi motion were presented in the same direction with the strength of phi motion varied with respect to that of reverse phi in terms of number of dots. The participants were given three choices based on their perceived motion direction – phi, reverse phi or transparent motion. Motion nulling should occur only when the strength of the opposite motion direction signals are equal. When one motion stimulus is stronger than the other, then the direction signaled by that stimulus is perceived. The participants reported a transparent motion at almost the same percentage of the trials as the phi motion until when the phi signal was 10% (25 dots) of reverse phi signal, after which the perception of phi motion became stronger and suppressed the perception of reverse phi and transparent motion. Perceptually, 25 to say 75 dots carrying the phi signal was equivalent to 250 dots carrying the reverse phi signal, which shows that reverse phi is weaker in the presence of phi motion. This is supported by the physiological study that measured the tuning curves of MT neurons for the reverse phi stimulus and found it to be lower in amplitude and broader in half-height tuning width than that of a phi stimulus, which suggests that the reverse phi elicits a weaker and a less directionally selective response compared to phi[96]. In Bours et al. (2007) study, the participants did not observe a transparent motion in a 2-way alternative forced choice (phi or reverse phi direction) and it required almost equal or slightly lower coherence levels of phi motion to neutralize the reverse phi motion[95]. For example, a 50% coherent reverse phi was nulled by a 45% coherent phi motion and a 100% coherent reverse phi stimulus was nulled by an 87% coherent phi motion. We did not use noise dots in our experiment unlike their study, which made the task easier to define the phi or reverse phi direction.

One participant's (MKP) responses were quite different from that of the average responses. They were similar except that the curves for phi and transparent motion flipped from what was observed in the rest of the participants. MKP reported transparent motion in most of the trials rather than phi motion, after the 10% cut off of phi signal. This could suggest that with adequate training, the participants can identify the transparent motion better, even when there is an imbalance in the strength of the motion in either direction. The transparent motion of reverse phi and phi motion percept is not immediately evident because of reverse phi being a weaker stimulus. In our study, we found that only around 25 dots with phi signal were enough to give a chance performance on reverse phi signal. In that case, for a phi motion with 250 dots, possibly a reverse phi motion with 2500 dots is required to perceive a transparent motion above chance level for an untrained participant. But this needs to be tested in future experiments. When this experiment was repeated with 2-way alternative forced choice paradigm on participant MKP similar to the Bours et al. study[95], the results were similar showing a chance performance of reverse phi and phi direction at 10% phi dots.

The experiment done by Bours et al.[95] was inspired by the nulling experiments in MAE. The illusory motion of the after-effects can be nulled by a real motion in the opposite direction to the adapting stimulus. Similarly, it was proposed that the reverse phi motion caused due to inhibitions can be nulled by the real phi motion in the opposite direction of the reverse phi percept. In our study, since reverse phi is suppressed or nullified essentially starting from when the phi signal dots are 10% or 30% of the reverse phi signal, we are not sure if we can conclude that reverse phi gives inhibitory response, which gets nullified by the increasing excitatory responses of phi motion with increasing number of dots carrying the phi signal. This is because there are many factors that influence the perception of transparent motion, which is due to excitatory responses. Selective attention to different components of the transparent motion alters the susceptibility of adaptation[153]. Since phi motion is a stronger stimulus than reverse phi, attention may be directed to phi signals.

We conclude that transparent motion was observed for both reverse phi and phi motion. Using phi and reverse phi motion percepts moving in the opposite directions, we found that reverse phi is a weaker stimulus that is dominated by a phi stimulus of a much weaker strength. These findings question the inhibition hypothesis of reverse phi proposed by Bours et al.[95]. Our results support the excitation hypothesis proposed by Mo-Koch[94] which suggests that the reverse phi motion is due to the excitation of neurons tuned in the opposite direction to the actual movement.

Chapter 5

Effect of Contrast Reversals on Perceived Speed

5.1 Overview

5.1.1 Background

When the contrast of the successive frames is reversed in an apparent motion stimulus, the perceived direction is reversed. This phenomenon is called reverse phi. Since the direction of motion is affected by the contrast reversals, we investigated whether it had an effect on the perceived speed.

5.1.2 Methods

Two RDK stimuli were presented for 0.5 second each in a sequential order with an inter-stimulus interval of 200 ms. First interval contained the standard stimulus with one of the following speeds - 18 deg/s, 24 deg/s or 34 deg/s and the second interval contained the test stimulus, which was 50%, 70%, 100%, 120%, 145% and 200% of the standard speed. The subject's task was to compare the speed of the two stimuli and indicate which of the two stimulus appeared to be faster. Four conditions were tested with phi and reverse phi motion being test and/or standard stimulus.

5.1.3 Results

The speed discrimination thresholds for phi motion were 5.8, 7 and 8 deg/sec for the standard stimuli 18, 24 and 34 deg/sec, respectively. It was not possible to obtain a speed discrimination threshold for reverse phi motion because slower test speeds were perceived as faster than the standard speeds and vice versa except for the 18deg/sec standard speed, where faster test speeds were perceived as slower. When reverse phi and phi motion were compared, reverse phi was perceived as faster in 96% (range 80-100%) of the trials when the phi motion was of the same speed as the reverse phi, despite changing the order of the presentation.

5.1.4 Conclusion

Slower speeds of reverse phi motion were perceived to be faster than the standard speeds due to the jerkiness inherent in the stimulus at slow speeds. The perceived speed of reverse phi was overestimated relative to phi motion when both were moving at the same speed.

5.1.5 Keywords

Speed discrimination, motion perception, reverse phi, phi motion, apparent motion, temporal forced choice

5.2 Introduction

Motion perception involves neural processes that provide not only the information about the direction of motion but also the speed, both of which are essential for navigating through the dynamic environment. There are neuro-pathological and electrophysiological evidence to the processing of motion direction and speed by the neurons in the middle temporal region of the brain[154,35,155–160,31,161,162]. Many neurons at MT are speed-tuned, with neurons representing fovea tuned to slow speeds. Lesions at these brain regions affected speed discrimination thresholds[35]. Both direction and speed information is determined by the same underlying neural mechanism – pooling/ integration of the responses from multiple band-limited local mechanisms[163,164,165,166,154].

There are many factors that affect perceived speed such as the contrast of the moving objects[167,168,169] , spatial frequency[19,170] , stimulus aperture size[171,172], motion adaptation [157], acceleration [173,174]. These changes are due to the alterations in the firing rate of MT neurons. Increasing the contrast of the moving sinusoidal grating increased its perceived speed particularly at slow standard speeds[167,168,175]. In other words, low contrast objects appeared to move slowly compared to the high contrast objects at temporal frequencies <8Hz [167]. At higher temporal frequencies of 16 Hz, decreasing the contrast increased the perceived speed. This contrast effect known as "Thompson effect"[169] is dependent on temporal frequency. At lower spatial frequencies of 1-4 cycles/deg, the perceived speed was faster while at higher spatial frequency, the perceived speed was slower[170]. This inverse relationship was consistent with the physiological responses of V1 area of the cat brain where the neurons tuned to higher spatial frequency preferred slow speeds and vice versa. Perceived speed has been found to be faster for smaller aperture size, an effect known as 'field-size effect'. When the aperture size and the size of the dots within the aperture were halved, the perceived speed doubled. The effect was seen but to a lesser extent even when the dot size was not scaled down[176,172].

Reversing the contrast at the successive frames of the moving object causes a reversed perception of the direction of motion[39]. This phenomenon called the reverse phi is due to the shift in the balance of motion energy towards the opposite direction. The direction reversal occurs due to the interactions between the ON and OFF channels of the visual system that arises as separate channels from bipolar cells of the retina and converges at V1. Previous studies show that reverse phi and phi are processed by similar mechanism since the spatio-temporal characteristic[66,90] and their sensitivity were similar[66]. However, since the direction and speed perception have similar neural mechanisms, we wanted to investigate whether the contrast reversal, which is the key characteristic of reverse phi stimulus, affected the perceived speed. Anstis[39] observed that smaller spatial displacements of the moving object resulted in a larger amplitude of reverse phi motion, in other words, faster perceived speed. In a rotating contrast-inverting random dot pattern, the dots closer to the center moved faster than the dots in the periphery because of the relatively smaller displacements at the center. He found that the more the overlap between the dots of opposite contrasts, more the speed of reverse phi, which suggests that the perceived speed increases with increasing dot size and decreasing displacements. He also found that as the speed of the dots increased, the perceived speed of the reverse phi motion decreased, indicating an inverse relationship. This was because the reverse phi phenomenon was not seen when the displacement was more than the size of the dot. We wanted to quantify the perceived speed differences of reverse phi and phi motion for different standard speeds and compare them. Firstly, we wanted to measure the speed discrimination thresholds for reverse phi motion and compare it with that of phi motion. Secondly, we wanted to assess whether reverse phi or phi motion was perceived as faster when both were presented at the same speed and if yes, how much faster.

5.3 Methods

The study was approved by the Institutional Review Board ORE # 22235. The stimuli were generated using Matlab 2016b Psychtoolbox package[114] (The MathWorks, Inc., Natick, Massachusetts, United States).

5.3.1 Subjects

Nine naïve and one experienced (MKP) human subjects participated in the study. All participants gave a written informed consent and all the procedures followed the tenets of Declaration of Helsinki. The study was approved by the Institutional review board of University of Waterloo. The subjects aged between 18 and 35 years with a visual acuity of 6/9 or more and normal contrast sensitivity as measured by Freiburg test were included. Any subject with ocular or brain related disease and those who did not give consent were excluded from the study.

5.3.2 Experimental setup

The experiment was presented on a 19.5” Dell E2014H monitor (1600x900 pixels, 8 bits/pixel, 60Hz) with NVIDIA GeForce GT 640 graphics card. The monitor was gamma corrected. The luminance output of the monitor was measured using SpectraScan Model PR-670 (Photo Research Inc., Chatsworth, California). The participants viewed the screen binocularly from a viewing distance of 60cm in a dim room and used a keyboard to respond. Each pixel subtended 0.03° from this viewing distance.

5.3.3 Stimuli

The stimuli used was sparse random dot kinematograms (RDK)[115] with 500 dots presented in a central 10x10deg aperture. The lifetime of the dots was 2 frames (33.4ms), after which the dead dots were repositioned in a random spot within the aperture. Likewise, the dots leaving the aperture were repositioned at random locations at the other edge of the aperture. The size of the dots was 0.13° in diameter. The luminance of white dots was 82 cd/m^2 and of black dots was 0.3 cd/m^2. The gray background had a luminance of 23 cd/m^2. The dot contrast was 99%. The temporal interval between two successive appearances of the dots was 16.7ms. The speed of the stimulus was achieved by varying the spatial displacement of the dots, which ranged from 0.2° (12 arc min) to 0.85° (51 arc min).

Figure 5-1 shows the psychophysical paradigm that was used to investigate how contrast reversals affected the perceived speed. The participant viewed a red fixation cross. Two RDK stimuli were presented for 0.5 second each in a sequential order with an inter-stimulus interval of 200 ms[177]. The subject’s task was to compare the speed of the two stimuli and indicate which of the two stimuli appeared to be faster. First interval contained the standard stimulus with one of the following speeds - 18 deg/s, 24 deg/s or 34 deg/s. The second interval contained the test stimulus, which was 50%, 70%, 100%, 120%, 145% and 200% of the standard speed. Hence, the test stimulus was either slower or faster than, or equal to the standard stimulus. In order to make the phi and reverse phi stimulus appear similar, half the number of dots were black in each frame. Reversed perception of the direction of motion for reverse phi stimulus was confirmed for all the speeds used in the study. For the standard speed of 18 deg/s, 50% test speed was not presented because reverse phi was not perceived at that test speed – a forward motion was perceived.

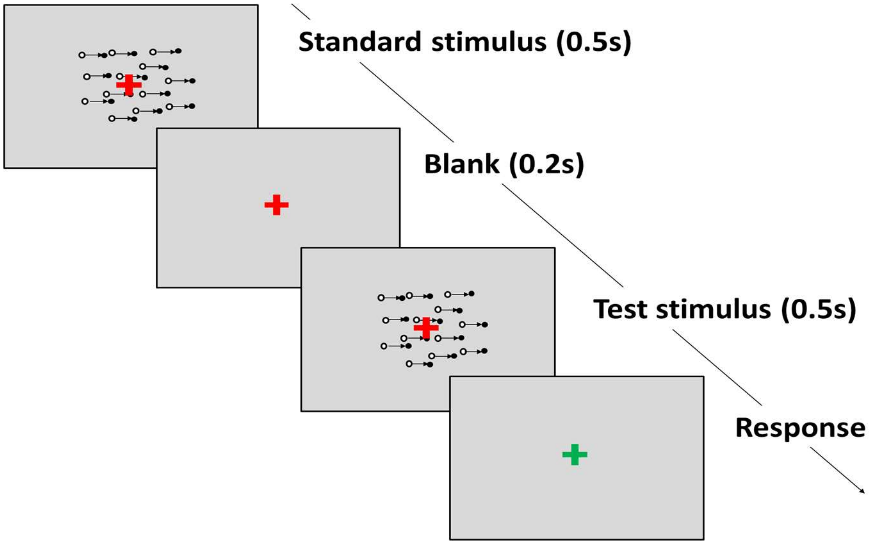


Figure 5-1 Psychophysical paradigm for speed discrimination experiment

Two types of motion stimuli were used: phi and reverse phi. The only difference between the two stimuli was the alternating contrast polarity in reverse phi stimulus. The standard and the test RDK stimulus could either be phi motion or reverse phi motion, which results in four possible comparisons: phi versus phi, reverse phi versus reverse phi, reverse phi versus phi, and phi versus reverse phi. All these four conditions were interleaved in a single experimental run and randomized. Each trial was repeated 10 times using the method of constant stimuli. Each standard speed was run as a separate experiment. Therefore, the total number of trials in a single run was 1 standard speed x 5 or 6 test speeds (dependent on the standard speed tested) x 4 comparison conditions x 10 repeats, resulting in 200 to 240 trials, which took a maximum of 9 mins (2.2 sec x 240 trials) to complete for each participant.

The direction of perceived motion was matched on both intervals and was in one of the four directions right, left, up or down. Using a 2-alternative temporal forced choice paradigm, the subjects responded to the fastest motion whether the first or the second motion stimulus was perceived to be faster, by pressing one of the two number keys on the keyboard. The next trial began immediately after the participant's response. No feedback was provided on the correctness of the response. This procedure was repeated for the other two standard speeds and the responses were collected.

5.3.4 Data Analysis

For all the conditions, the percentage of the trials in which the test stimulus was perceived as being faster was calculated for each combination of standard and test stimuli. For the reverse phi:phi comparison condition, the percentage of trials in which reverse phi was perceived as faster was also calculated in addition to the percentage of test speeds that appeared as faster. A sigmoid curve, (1/(1+e^-((x-xo)/b))) was fitted to the data, where xo is the threshold, and b is the slope. The point of subjective equality (PSE) was calculated corresponding to the 50% probability of the test stimulus being faster. The speed discrimination threshold was the mean of lower and upper discrimination thresholds, which were defined as the difference in the speed between PSE and the 25% probability, and the 75% probability, respectively. The constant error, i.e., the difference between the actual standard speed and the PSE was calculated. We wanted to compare the discrimination thresholds between reverse phi and phi motion. The alpha error was set at 5% for the statistical significance.

5.4 Results

Ten subjects participated in the study. The mean age was 30±2years. We assessed the ability to discriminate the speeds of reverse phi and phi motion, and measured the speed discrimination thresholds for both. The participants reported a motion direction that was opposite to the physical displacement of the reverse phi stimulus for all the speeds used in the study.

5.4.1 Like comparisons: Phi versus Phi and Reverse Phi versus Reverse Phi

Figure 5-2 shows the psychometric functions of the first two comparison conditions, phi:phi and reverse phi:reverse phi. For phi:phi comparison, the subjects were able to discriminate between the slower and the faster speeds, which resulted in a sigmoid psychometric function. The subjects overestimated the speed slightly for all the standard speeds. The constant error was 3.4 for 18deg/sec, 4.6 for 24deg/sec, and 2.7 for 34deg/sec. The average speed discrimination threshold for phi:phi comparison was 5.8, 7, and 8 deg/sec for 18, 24, and 34 deg/sec standard speeds, respectively. Contrary to phi:phi comparison, in reverse phi:reverse phi comparison, the slower test speeds of reverse phi were perceived to be faster than the standard speeds, which was consistent across all standard speeds (Figure 5-2). In addition, the faster speeds of reverse phi were also chosen to be faster than the standard stimulus, except for 18 deg/s standard speed at which faster test speeds were perceived as slower. Due to this lack of discriminability, we could not plot the sigmoid function for reverse phi:reverse phi comparison.

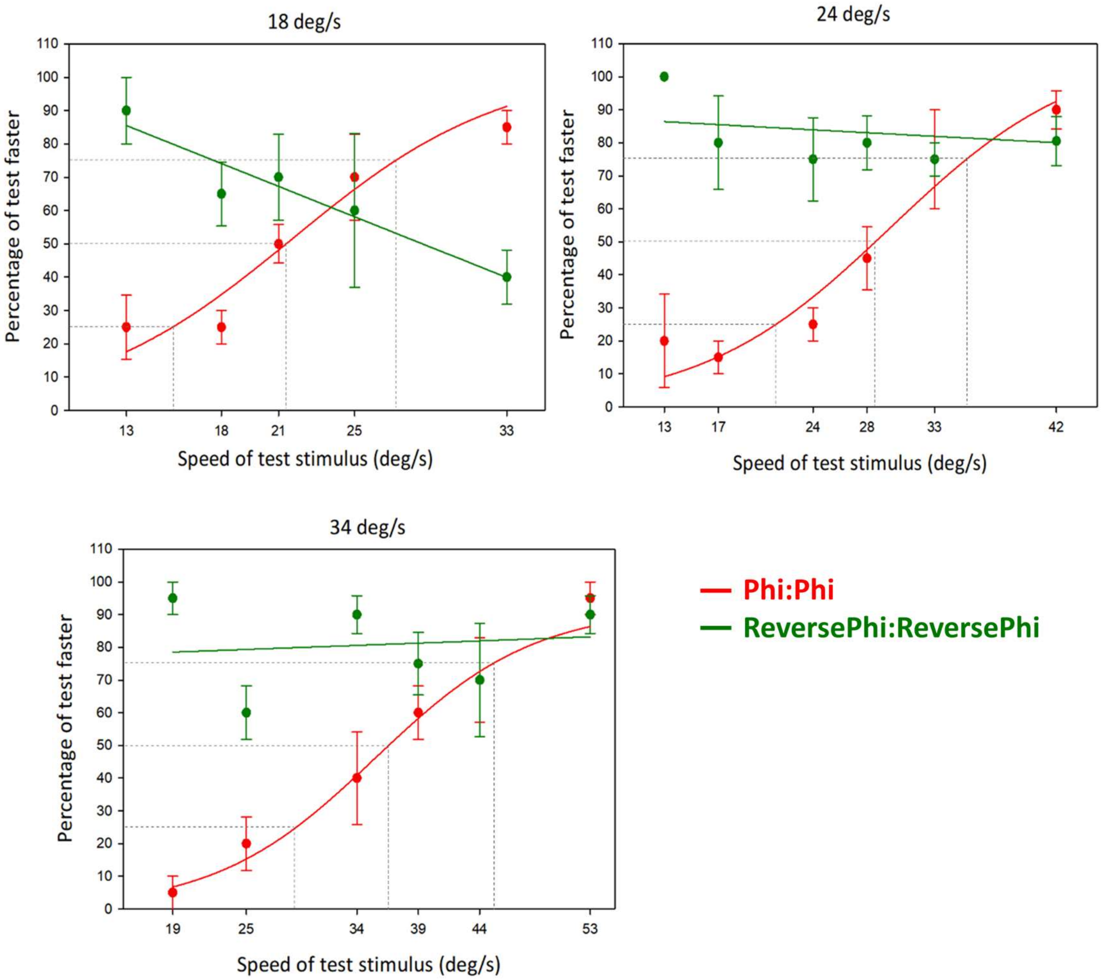


Figure 5-2 Percentage of faster response for Phi:Phi and Reverse Phi:Reverse Phi comparisons. Mean of 10 participants is plotted and the error bars indicate standard error.

5.4.2 Cross comparisons: Reverse Phi versus Phi motion

When the perceived speed was compared between reverse phi and phi motion, we reversed the order of the motion types and presented the trials as two separate conditions. In the third comparison condition (reverse phi: phi), when reverse phi was presented first as the standard stimulus followed by the phi motion as the test stimulus, the faster speeds of phi motion was perceived as slower than the reverse phi standard speed (Figure 5-3). Even when the phi motion test stimulus was presented twice as fast as the reverse phi motion, the reverse phi was still perceived to be faster but the percentage of trials in which this occurred reduced for faster standard speeds. At 34 deg/s, we could plot a psychometric function and there was a clear rightward shift of the PSE, which indicates that the perceived speed of reverse phi was overestimated by 42%. This means that the speed of phi stimulus had to be 42% more than that of reverse phi stimulus to be perceived as having the same speed as the reverse phi stimulus. This magnitude of overestimation could not be computed for other standard speeds because the PSE couldn't be spotted for those standard speeds.

In the fourth comparison condition (phi:reverse phi), irrespective of the speed of the reverse phi test stimulus compared to the standard phi motion, reverse phi test stimulus was perceived to be faster in almost 100% of the trials (Figure 5-3). When the phi motion was of the same speed as the reverse phi motion, the participants perceived the reverse phi motion to be faster in 93.3%±4%of the trials. This was consistent across all reference speeds.

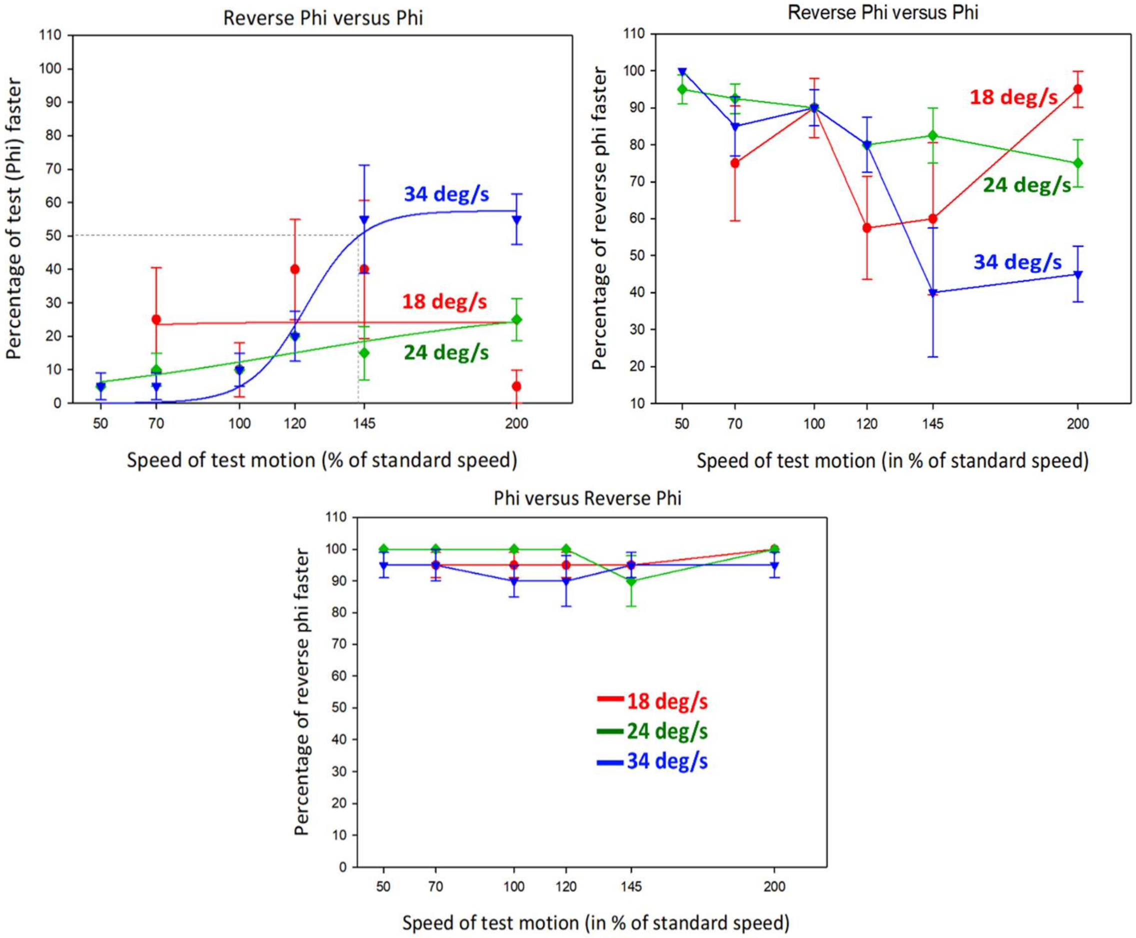


Figure 5-3 Percentage of faster response for Reverse Phi:Phi and Phi:Reverse Phi comparisons. Mean of 10 participants is plotted and the error bars indicate standard error.

5.5 Discussion

In this study, the speed discrimination ability was assessed for reverse phi and phi motion and the perceived speed differences between reverse phi and phi were quantified. We found that the participants could not discriminate the speeds of reverse phi especially at the faster standard speeds of 24 deg/sec and 34 deg/sec. However, they were able to discriminate the speeds of phi motion – the slower test speeds appeared to be slower and the faster test speeds appeared to be faster than the standard speeds. When the phi and the reverse phi motion were presented at the same speed, the participants perceived reverse phi as faster in about 93% of trials, despite reversing the order of the presentation.

When both the standard and test speeds were reverse phi motion, at the standard speed of 18 deg/sec, the slower test speeds of reverse phi were perceived as faster and the faster test speeds were perceived as slower than the standard speed. Similar findings were reported by Anstis[39] who observed that the smaller displacements of reverse phi stimulus, which corresponds to slow speeds, were perceived to be faster and vice versa. He observed these perceived speed differences in successively presented positive and negative images, and rotating random dot patterns. He noted that this inverse relationship was due to the interaction between dot size and displacement because as the displacement increased more than the dot size, the reverse phi motion disappeared. In our study, we used random-dot kinematograms and found that this inverse relationship between the actual speed and the perceived speed was true, but only for the slower standard speed of 18 deg/sec. For a grating stimulus of a period p, a displacement of d with contrast reversal produces an apparent displacement of p/2-d in the opposite direction. When the displacement is small, this apparent displacement increases more than when the displacement is large. The apparent displacement for a given physical displacement would vary in a stimulus such as a random dot kinematogram because of multiple spatial frequencies inherent in it. However, these several apparent displacements would integrate together to provide an average displacement[154,165,166].

At higher standard speeds of 24 and 34 deg/sec, both smaller and larger displacements, i.e., slower and faster test speeds, were perceived as faster than the standard speeds. In other words, there was no speed discriminability at higher standard speeds of reverse phi. Anstis[39] reported that at faster speeds, the perceived speed increased as the physical speed increased because of an artifact of the dot appearing as a streak at high speeds. This streak effect cannot explain why faster test speeds of reverse phi were perceived as slower at 18 deg/sec standard speed. Sato[90] calculated the motion amplitude of reverse phi and phi motion using model simulations and found that for reverse phi, the motion amplitude was higher for small displacements and as the displacement increased, it dropped to zero at around 20min of arc[90].

This reduction in the motion amplitude at larger displacements explains why faster test speeds of reverse phi were slower than the standard speed of 18deg/sec. However, it does not explain why this relationship reversed at higher standard speeds.

Our participants reported that the reverse phi stimulus had jerky movement at slow speeds. We speculate that the flicker inbuilt in the slow speeds of reverse phi motion made it appear as faster because the effect of contrast on perceived speed is due to its effect on the perceived flicker[178]. As the contrast of the grating was decreased, the perceived flicker/temporal frequency decreased, thereby the perceived speed also decreased at lower temporal frequencies[178], although there is evidence for differential effects of contrast on both the parameters[179]. However, McKee et al.[180] and Pasternak[181] support the idea that the speed discriminations are not derived from flicker-rate discriminations. Hence, the perceived speed is not being extracted from the flicker information or vice versa[19,180]. A recent study[181] shows that the speed of the moving object depends on its spatial and temporal frequency properties, which is how the hMT+ region encodes the speed. Measurement of these frequencies for reverse phi and phi motion would indicate the differences between them.

For phi motion, the participants demonstrated the ability to discriminate speed unlike the reverse phi motion. The PSE decreased with increasing standard speeds. This implies that with increasing speeds or displacements, the deviation of the perceived speed from the actual speed is decreasing. Sato[90] found that the motion amplitudes for phi motion almost matched the actual displacement only at very small displacements. The motion amplitudes increased and slightly deviated from the actual displacement as the displacement increased until 10 min of arc (0.17 deg) where it reached the peak. After that, the amplitudes reduced and reached zero at 20 min of arc (0.33 deg).

In our study, we presented the standard speed first followed by the test stimulus. There is a possibility of a response bias where the participant could choose the 1st or the 2nd stimulus consistently, most likely the 2nd stimulus because of the memory fade out inherent in the temporal-forced choice paradigm. However, when we compared reverse phi and phi motion with reverse phi being presented first, reverse phi stimulus was perceived as faster. This finding was observed irrespective of the order of presentation of the reverse phi stimulus. Using the gradient scheme proposed by Marr-Ullman[52], Sato[90] calculated the speed of the reverse phi and phi RDK and found that the distribution of speed was more uniform at smaller displacements for phi motion than reverse phi. Simulations using the directed matching scheme, which gives reliable estimates of speed or motion amplitude showed that the mean motion amplitudes for reverse phi was higher at smaller displacements than phi motion[90,105]. On the contrary, the simulations based on nearest matching scheme predicted lower motion amplitudes for reverse phi at smaller displacements. It predicted the amplitudes similar to directed matching scheme for phi motion. However, since it also predicted the direction reversal for reverse phi stimulus at a lower probability over small displacements, directed matching scheme was considered a better predictor of the speed and direction of reverse phi motion. The distribution of speed for reverse phi motion was not so coherent compared to phi motion, which was also reported by Adelson and Bergen[65].

There are many factors that affect the perceived speed including the stimulus contrast[167,168,169], size of the object (size-speed illusion)[182], motion adaptation[157], acceleration[173,174], stimulus aperture size[154,172], and eye movements[182]. Our study shows that the contrast reversal in the moving pattern is one of the factors that can lead to misperception of the speed. Since the random dot pattern is a more complex stimulus that varies in spatial and temporal frequencies, the experiments could be repeated using a simpler stimulus such as a grating to assess the reproducibility of the study. Also, for reverse phi at faster reference speeds, more test speeds could be included to possibly find the point of subjective equality or a method of adjustments could be used to manipulate the speed of the stimulus to find the amount of overestimation.

In summary, slower speeds of reverse phi motion were perceived to be faster than the standard speeds. This could be associated with the jerkiness inherent in the stimulus at slow speeds. The perceived speed of reverse phi was overestimated relative to phi motion when both were moving at the same speed.

Chapter 6

Conclusion and Future direction

6.1 Summary of the dissertation

In this dissertation, I have discussed how the motion system processes a counter-intuitive phenomenon called the reverse phi. Earlier studies on reverse phi motion thought of the direction reversal as trivial because a reverse phi stimulus simply shifts the balance of the motion energy in the opposite direction, to which an appropriate motion detector would respond. Recent studies have proposed that the direction reversal is not merely inherent in the stimulus but has a neurological basis. Some studies have proposed that the interactions between ON and OFF pathways result in the inhibition of neurons selective for the same direction of the physical displacement of the stimulus, thus resulting in the reversed perception of motion direction. Other studies contradict the idea of such interactions. Based on the results from our experiments, we suggest that there could be inefficiencies in the combination of the ON and OFF pathways making the reverse phi motion stimuli a weaker stimulus to the motion system when compared to the phi motion stimuli. In addition, there is a possibility of perceiving transparent motion using reverse phi motion, which questions the inhibition hypothesis. Since the direction and speed processing have similar neural mechanisms, it was interesting to look at the effect of the contrast reversals on the perceived speed. We found that the reverse phi motion was perceived as faster compared to phi motion and we quantified this effect in our study.

In chapter 2, we measured the spatio-temporal characteristics and the sensitivity of the motion system to reverse phi motion and looked at how the results compared with the regular phi motion. We used random dot kinematograms with various combinations of spatial and temporal offsets and found that the spatial and temporal characteristics of reverse phi and phi motion overlap for a small range of spatial and temporal offsets, suggesting a common short-range mechanism. However, reverse phi responses decreased more than phi responses at larger displacements and longer temporal intervals, suggesting a relatively stronger influence of long-range mechanism on reverse phi than phi motion in these extreme combinations of spatial and temporal offsets. The maximum spatial limit, Dmax, was smaller for reverse phi than for phi motion. In terms of the motion sensitivity, the reverse phi motion had lower sensitivity compared to phi motion, suggesting inefficiency in the combination of positive and negative contrasts by ON and OFF channels, respectively.

In chapter 3, we measured the spatio-temporal characteristics and the motion sensitivity for the two motion types at the peripheral location centered at 15 deg. We used the same stimulus but scaled up the dot size to account for the peripheral loss in spatial resolution. Overall results indicated that the measured parameters were similar between the central and peripheral presentations for both phi and reverse phi motion, suggesting that the mechanism involving the short-range motion is unaffected with eccentricity, when the dot size scaling was used. The differences seen in these parameters between phi and reverse phi motion was maintained or even widened at the periphery.

In chapter 4, we looked at the possibility of motion transparency in reverse phi stimulus. Our participants reported seeing transparent motion for both reverse phi and phi motion. Using phi and reverse phi motion percepts moving in the opposite directions, we found that reverse phi is a weaker stimulus that is dominated by a phi stimulus of a much weaker strength. These findings question the inhibition hypothesis of reverse phi which says that the reverse phi is due to the inhibition of neurons tuned in the direction of actual movement. Our results support the excitation hypothesis that reverse phi is due to the excitation of neurons tuned in the opposite direction to the actual movement.

In chapter 5, we measured the perceived speed differences between reverse phi and phi motion and quantified perceived speed differences between reverse phi and phi motion. Our participants lacked the ability to discriminate the faster speeds of reverse phi from the slower speeds, particularly at higher standard speeds. At the lowest standard speed that we used, faster speeds of reverse phi were perceived as slower and vice versa. Such inability to discriminate the speed was not observed for phi motion. Reverse phi was perceived as faster than phi motion by about 28% when it was moving at 34 deg/s. These findings suggest that speed perception, which is a higher level process in the motion system, is affected by contrast reversals, which is a low-level parameter.

6.2 Future directions

There are a lot of avenues for improvement and further extension of these experiments. Obviously, there are limitations to conclusions that one can draw using pure psychophysical studies in terms of the neural mechanisms underlying the percepts. Since our findings, such as the weaker sensitivity to reverse phi and motion transparency in reverse phi, contradict the previous studies, further experiments should be done using transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (tDCS) to alter the amounts of inhibition or excitation at V1/MT and observe the probability of reverse phi perception. The transcranial stimulation techniques are non-invasive, and causes reversible modulation of the cortical activity in the brain. These tools have been successfully used in the study of the relationship between the brain function and the behavior particularly to study memory, attention, motor processes, and visual perception, by reversibly inducing what is called 'virtual brain lesion'[183–187].

Therefore, using these techniques to study reverse phi motion could possibly tease out the neural mechanism.

In terms of improvements in the experiments that were conducted, the following modifications could be made. The basic random dot stimulus used at higher temporal intervals could be rendered smoother and to flow without obvious flicker by repeating the preceding frame in place of an inter-stimulus interval. This could possibly improve the perception of reverse phi stimulus as well as phi stimulus. In the perceived speed experiment comparing reverse phi and phi motion, lower standard speeds did not give a sigmoid curve to identify the point of subjective equality, which could quantify the amount of overestimation of reverse phi speed. Alternatively, a method of adjustment could be employed by which the participants could adjust the speed of the stimulus to match with the standard stimulus. The same methodology could be employed for understanding the speed discrimination ability for reverse phi. A model could be devised to predict the perceived speed for reverse phi.

The reverse phi stimulus is a motion illusion that gives an opposite percept of the direction in which the stimulus is actually moving. Therefore, the stimulus can be easily incorporated into motion perception tasks such as a motion discrimination, as a catch trial along with regular motion stimulus to reduce the response bias.

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Appendix A

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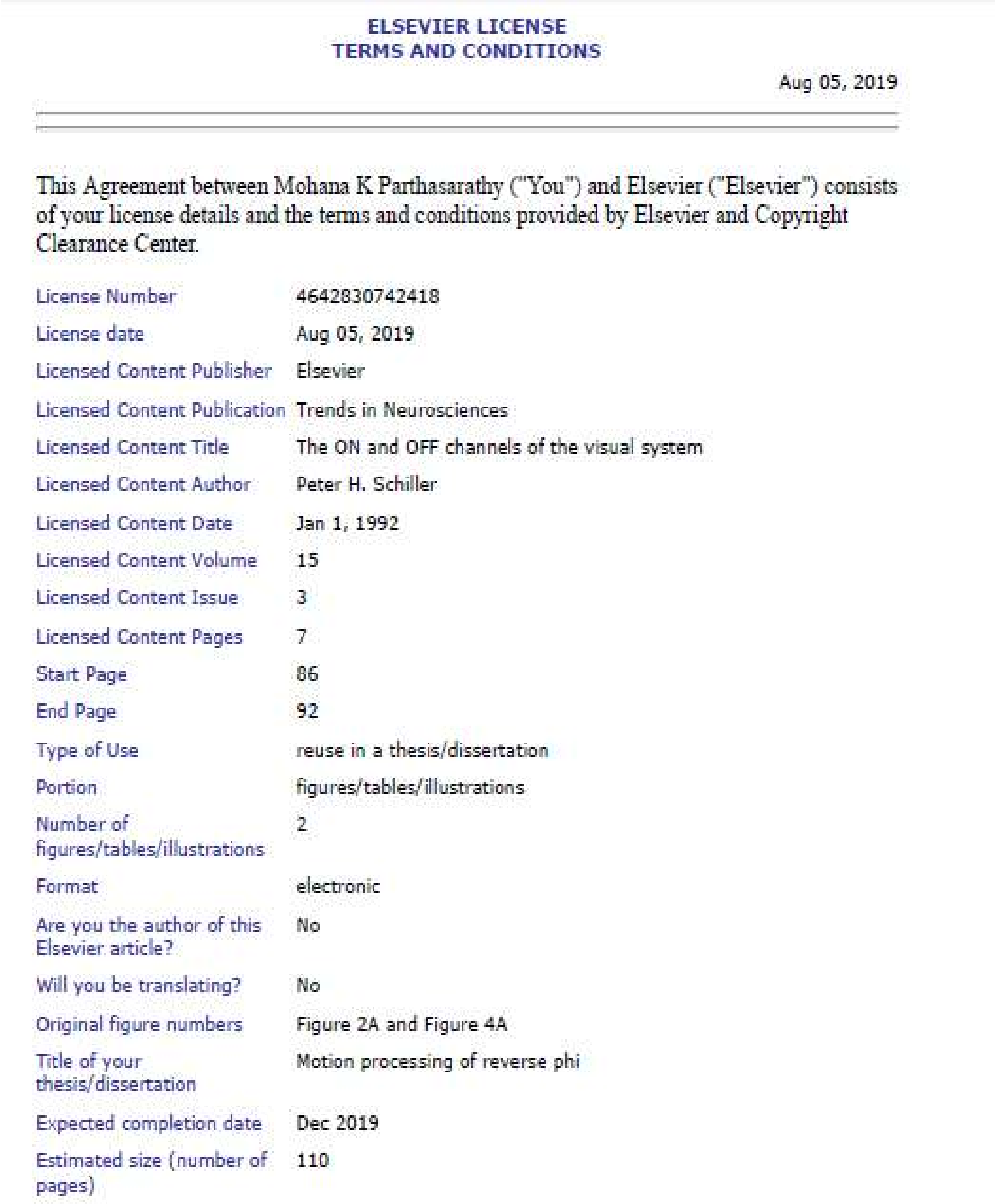

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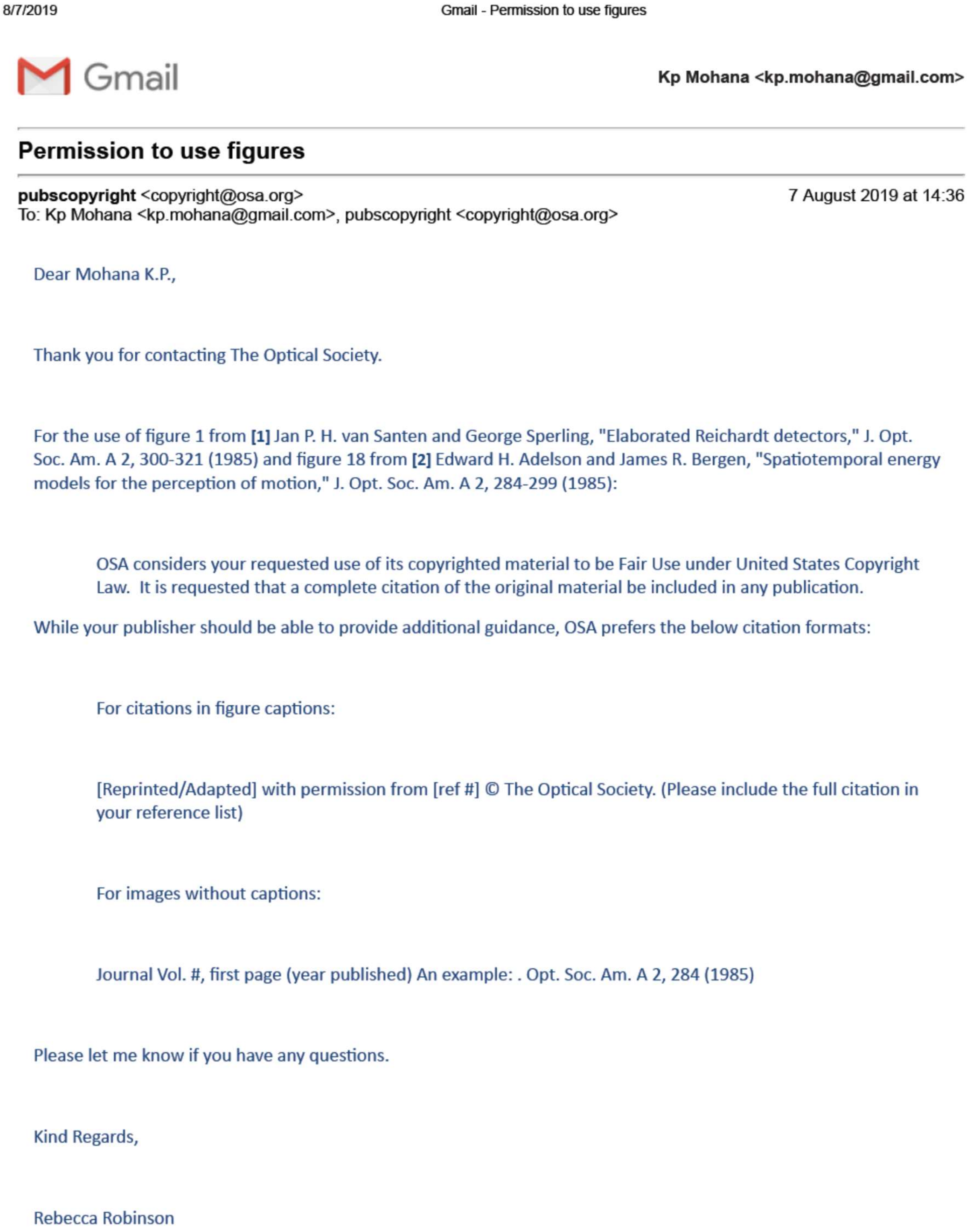

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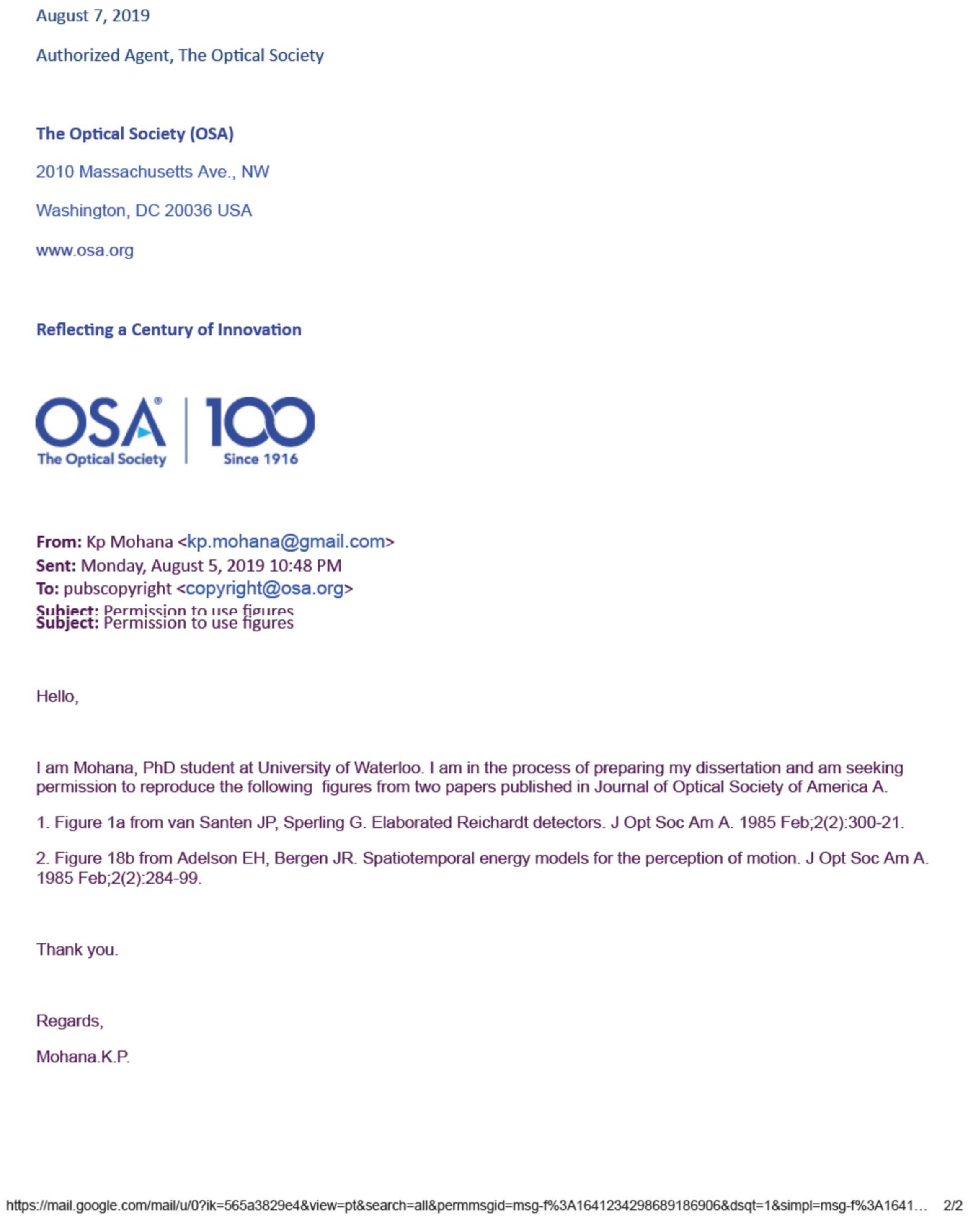

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Thank you.

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Mohana.K.P.

Appendix B
Conference presentations

1. Mohana Kuppuswamy Parthasarathy, Vasudevan Lakshminarayanan; Reverse Phi: Effect of Contrast Reversals on Perceived Speed. *Journal of Vision* 2019;19(10):286. doi: 10.1167/19.10.286. Vision Science Society (VSS) 2019, Florida, USA.

2. Mohana Kuppuswamy Parthasarathy, Vasudevan Lakshminarayanan. Perception of Motion transparency: Reverse Phi. Association for Research in Vision and Ophthalmology (ARVO) 2019, Vancouver, British Columbia, Canada. (Poster abstract # 3147026)

3. Mohana Kuppuswamy Parthasarathy, Vasudevan Lakshminarayanan. Interocular Presentation of Reverse Phi, American Academy of Optometry (AAO) 2018, San Antonio, Texas, USA. (Poster abstract # 3024409)

4. Mohana Kuppuswamy Parthasarathy, Vasudevan Lakshminarayanan. Human Motion Processing in Reverse Phi – Effect of Eccentricity. Invest. Ophthalmol. Vis. Sci. 2018;59(9):1277. Association for Research in Vision and Ophthalmology (ARVO) 2018, Honolulu, Hawaii, https://iovs.arvojournals.org/article.aspx?articleid=2689757. (Poster abstract # 2916177)

Appendix C

Codes for Experiments

A) Phi motion – Spatio-temporal characteristics:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Phi motion. Subjects have
to response to the direction of
% motion of dots by pressing up,down, left, right arrow keys.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS
%
clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
```

```
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;


%%% RDK parameters
DotColor=White;
Ndots=500;
DotSize=5;
DotSpeed=240;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);


%dot lifetime
dots_lifetime=2;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%Positions of the dots
dots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
dots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;


%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];
```

```
WhiteDotStart=1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );

keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TempStepStart=1;
TempStepEnd=4;
ConstStimN = str2double(nCS);
TempStepBasic=TempStepStart:TempStepEnd;
TempStepVect=TempStepBasic(randperm(length(TempStepBasic)));

DotSpeedStart=1;
DotSpeedEnd=11;
DotSpeedBasic=DotSpeedStart:2:DotSpeedEnd;
DotSpeedBasic=DotSpeed*DotSpeedBasic;
DotSpeedRep=repmat(DotSpeedBasic,1,ConstStimN);
DotSpeedVect=DotSpeedRep(randperm(length(DotSpeedRep)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
HideCursor();
resultsAll=[];
for Ntrialsi=1:length(TempStepVect)
    TempStep=TempStepVect(Ntrialsi);
    BlackDotStart=TempStep+WhiteDotStart;
    WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
    BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
    DispFrames=BlackDotStart-1:TempStep:nFrames;

    Color=[1 2];
    ColorFramesBasic=zeros(1,nFrames);
```

```
    ColorFramesBasic(WhiteDotsFrames)=Color(1);
    ColorFramesBasic(BlackDotsFrames)=Color(1);
    lenColorFrames=length(ColorFramesBasic);
    ColorFrames=zeros(Ndots,lenColorFrames);
    for i=2:Ndots
        ColorFrames(1,:)=ColorFramesBasic;
        if rem(i,2)==0
            ColorFrames(i,:)=2;
        else
            ColorFrames(i,:)=1;
        end
    end

    for Ntrialsj=1:length(DotSpeedVect)
        DotSpeed=DotSpeedVect(Ntrialsj);
        DotDirectionN=Shuffle([0 90 180 270]);
        DotDirection=DotDirectionN(3);

        %step size of displacement
        dX=DotSpeed*sind(DotDirection)/Hertz;
        dY=DotSpeed*cosd(DotDirection)/Hertz;

        for Frames=1:nFrames

            % for drawing fixation cross on every frame
            Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);


            for j=1:Ndots
                % for drawing dots in respective frames
                if ColorFrames(j,Frames)==1
                    Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColor,[],1);
                elseif ColorFrames(j,Frames)==2
                    Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColorRev,[],1);
                end
            end

            Screen('Flip', MainWin);

            if any(DispFrames(:)== Frames)
                dots_X= dots_X+(dX);
                dots_Y= dots_Y+(dY);

                % to prevent dots from moving outside the aperture.
                dots_X(dots_X>xRight)=dots_X(dots_X>xRight)-Aperture_r*2;
                dots_X(dots_X<xLeft)=dots_X(dots_X<xLeft)+Aperture_r*2;
                dots_Y(dots_Y<yTop)=dots_Y(dots_Y<yTop)+Aperture_r*2;
                dots_Y(dots_Y>yBottom)=dots_Y(dots_Y>yBottom)-Aperture_r*2;


                %%limited lifetime dots
                dots_life = dots_life+1;
```

```
                deadDots = mod(dots_life,dots_lifetime)==0;
                dots_X(deadDots) = (rand(1,sum(deadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
                dots_Y(deadDots) = (rand(1,sum(deadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;
            end
        end

  %%%for keyboard responses:
    Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
    Screen('Flip', MainWin);

    keyIsDown = 0;
    StartTime = GetSecs;
    correct=0;
    RT=0;

    while 1
        [keyIsDown, timeSecs, keyCode] = KbCheck;
        FlushEvents('keyDown');
        if keyIsDown
            nKeys = sum(keyCode);
            if nKeys==1
                if
keyCode(UpArrow)||keyCode(DownArrow)||keyCode(LeftArrow)||keyCode(RightArrow)
                    RT = (timeSecs-StartTime);
                    keypressed=find(keyCode);
                    break;
                elseif keyCode(EscapeKey)
                    ShowCursor; Screen('CloseAll'); return
                end
                keyIsDown=0; keyCode=0;
            end
        end
    end


  if (keypressed==CorrKeys(4) && DotDirection == 180) ||
(keypressed==CorrKeys(3) && DotDirection == 0) || (keypressed==CorrKeys(2) &&
DotDirection == 270)|| (keypressed==CorrKeys(1) && DotDirection == 90)
        correct = 1; % reverse phi
    elseif (keypressed==CorrKeys(3) && DotDirection == 180) ||
(keypressed==CorrKeys(4) && DotDirection == 0) || (keypressed==CorrKeys(1) &&
DotDirection == 270)|| (keypressed==CorrKeys(2) && DotDirection == 90)
        correct = 0; % phi
    else
        correct=2; %guessing
    end

 % write the data
    results=[ConstStimN DotSpeed DotDirection StartTime timeSecs RT
keypressed TempStep correct];
    resultsAll=[resultsAll;results];

    WaitSecs(0.5);
```

```
    end
 end

resultsHead = {'nCS' 'DotSpeed' 'dX' 'dY' 'DotDirection' 'StartTime'
'timeSecs' 'RT' 'keypressed' 'TempStep' 'correct'};
xlswrite(outputname,resultsHead,1,'A1');
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```

B) Reverse Phi motion – Spatio-temporal characteristics.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Reverse Phi motion.
Subjects have to response to the direction of
% motion of dots by pressing up,down, left, right arrow keys.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
```

```
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;


%%% RDK parameters
DotColor=White;
Ndots=500;
DotSize=5;
DotSpeed=240;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);


%dot lifetime
dots_lifetime=2;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%Positions of the dots
dots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
dots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;


%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
```

```
Fix_XY=[Fix_X; Fix_Y];


WhiteDotStart=1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );

keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

TempStepStart=1;
TempStepEnd=4;
ConstStimN = str2double(nCS);
TempStepBasic=TempStepStart:TempStepEnd;
TempStepVect=TempStepBasic(randperm(length(TempStepBasic)));

DotSpeedStart=1;
DotSpeedEnd=13;
DotSpeedBasic=DotSpeedStart:2:DotSpeedEnd;
DotSpeedBasic=DotSpeed*DotSpeedBasic;
DotSpeedRep=repmat(DotSpeedBasic,1,ConstStimN);
DotSpeedVect=DotSpeedRep(randperm(length(DotSpeedRep)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HideCursor();
resultsAll=[];
for Ntrialsi=1:length(TempStepVect)

    TempStep=TempStepVect(Ntrialsi);
    BlackDotStart=TempStep+WhiteDotStart;
    BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
    WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
```

```
    DispFrames=BlackDotStart-1:TempStep:nFrames;


    Color=Shuffle([1 2]);
    ColorFramesBasic=zeros(1,nFrames);
    ColorFramesBasic(WhiteDotsFrames)=Color(1);
    ColorFramesBasic(BlackDotsFrames)=Color(2);

    lenColorFrames=length(ColorFramesBasic);
    ColorFrames=zeros(Ndots,lenColorFrames);
    for i=2:Ndots
        ColorFrames(1,:)=ColorFramesBasic;
        ColorFrames(i,:)=circshift(ColorFrames(i-1,:),lenColorFrames-1,2);
    end

    for Ntrialsj=1:length(DotSpeedVect)
        DotSpeed=DotSpeedVect(Ntrialsj);

        DotDirectionN=Shuffle([0 90 180 270]);
        DotDirection=DotDirectionN(3);

        %step size of displacement
        dX=DotSpeed*sind(DotDirection)/Hertz;
        dY=DotSpeed*cosd(DotDirection)/Hertz;

        for Frames=1:nFrames

            % for drawing fixation cross on every frame
            Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);

            % for drawing dots in respective frames
            for j=1:Ndots
                if ColorFrames(j,Frames)==1
                    Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColor,[],1);
                elseif ColorFrames(j,Frames)==2
                    Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColorRev,[],1);
                end
            end


            Screen('Flip', MainWin);


            if any(DispFrames(:)== Frames)
                dots_X= dots_X+(dX);
                dots_Y= dots_Y+(dY);

                % to prevent dots from moving outside the aperture.
                dots_X(dots_X>xRight)=dots_X(dots_X>xRight)-Aperture_r*2;
                dots_X(dots_X<xLeft)=dots_X(dots_X<xLeft)+Aperture_r*2;
                dots_Y(dots_Y<yTop)=dots_Y(dots_Y<yTop)+Aperture_r*2;
```

```
                dots_Y(dots_Y>yBottom)=dots_Y(dots_Y>yBottom)-Aperture_r*2;


                %%limited lifetime dots
                dots_life = dots_life+1;
                deadDots = mod(dots_life,dots_lifetime)==0;

                dots_X(deadDots) = (rand(1,sum(deadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
                dots_Y(deadDots) = (rand(1,sum(deadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;
            end


        end

  %%%for keyboard responses:
    Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
    Screen('Flip', MainWin);

    keyIsDown = 0;
    StartTime = GetSecs;
    correct=0;
    RT=0;

    while 1
        [keyIsDown, timeSecs, keyCode] = KbCheck;
        FlushEvents('keyDown');
        if keyIsDown
            nKeys = sum(keyCode);
            if nKeys==1
                if
keyCode(UpArrow)||keyCode(DownArrow)||keyCode(LeftArrow)||keyCode(RightArrow)
                    RT = (timeSecs-StartTime);
                    keypressed=find(keyCode);
                    break;
                elseif keyCode(EscapeKey)
                    ShowCursor; Screen('CloseAll'); return
                end
                keyIsDown=0; keyCode=0;
            end
        end
    end


    if (keypressed==CorrKeys(4) && DotDirection == 180) ||
(keypressed==CorrKeys(3) && DotDirection == 0) || (keypressed==CorrKeys(2) &&
DotDirection == 270)|| (keypressed==CorrKeys(1) && DotDirection == 90)
        correct = "RP"; % reverse phi
    elseif (keypressed==CorrKeys(3) && DotDirection == 180) ||
(keypressed==CorrKeys(4) && DotDirection == 0) || (keypressed==CorrKeys(1) &&
DotDirection == 270)|| (keypressed==CorrKeys(2) && DotDirection == 90)
        correct = "Phi"; % phi
    else
        correct=2; %guessing
```

```
    end

keypress=convertCharsToStrings(KbName(keypressed));
 % write the data
    results=[ConstStimN DotSpeed dX dY DotDirection StartTime timeSecs RT
keypress TempStep correct];
    resultsAll=[resultsAll;results];

    WaitSecs(0.5);

    end

end

resultsHead = {'nCS' 'DotSpeed' 'dX' 'dY' 'DotDirection' 'StartTime'
'timeSecs' 'RT' 'keypress' 'TempStep' 'correct'};
xlswrite(outputname,resultsAll,1,'A2');


Screen('CloseAll');
```

C) Phi motion – Motion Coherence experiment.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Phi motion coherence
experiment. Subjects have to response to the direction of
% motion of dots by pressing up,down, left, right arrow keys.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
```

```
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;


%%% RDK parameters
Ndots=500;
DotSize=5;
DotSpeed=480;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);
DotColor=White;

%dot lifetime
dots_lifetime=5;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);
```

```
%Temp interval
TempStep=1;

format shortG
%Positions of the dots
dots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
dots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;

%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];

%%%For Reverse phi
WhiteDotStart=1;
BlackDotStart=TempStep+WhiteDotStart;
BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
DispFrames=BlackDotStart-1:TempStep:nFrames;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Experimental instructions, wait for a spacebar response to start

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );

keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%VARIABLE STUDIED
ConstStimN = str2double(nCS);
DotCoherenceBasic=[0 0.05 0.075 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.7
1];
DotCoherenceRep=repmat(DotCoherenceBasic,1,ConstStimN);
```

```
DotCoherenceVect=DotCoherenceRep(randperm(length(DotCoherenceRep)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

resultsAll=[];
for Ntrialsi=1:length(DotCoherenceVect)
    DotCoherence=DotCoherenceVect(Ntrialsi);
    CohDotsN=ceil(DotCoherence*Ndots);
    InCohDotsN=Ndots-CohDotsN;

    Color=[1 2];
    ColorFramesBasic=zeros(1,nFrames);
    ColorFramesBasic(WhiteDotsFrames)=Color(1);
    ColorFramesBasic(BlackDotsFrames)=Color(1);
    lenColorFrames=length(ColorFramesBasic);
    ColorFrames=zeros(Ndots,lenColorFrames);
    for i=2:Ndots
        ColorFrames(1,:)=ColorFramesBasic;
        if rem(i,2)==0
            ColorFrames(i,:)=2;
        else
            ColorFrames(i,:)=1;
        end
    end

    %for dot directions in any of the 4 directions
    DotDirectionN=Shuffle([0 90 180 270]);
    DotDirection=DotDirectionN(3);

    dXCoh=DotSpeed*sind(DotDirection)/Hertz;
    dYCoh=DotSpeed*cosd(DotDirection)/Hertz;
    %for moving the dots
    CohPix=dots_X(randperm(numel(dots_X),CohDotsN));
    %to find the index of coherent dots in dots_X
    [tf,loc]=ismember(dots_X,CohPix);
    idx=[1:length(dots_X)];
    idxC=idx(tf);
    CohIdx=idxC(loc(tf));
    %to find the incoherent dots pixels and index in X-axis and Y-axis
    [InCohPixX, InCohIdx]=setdiff(dots_X,CohPix);
    InCohPixY=dots_Y(InCohIdx);
    % random directions for incoherent dots
    RandDir=rand(1,InCohDotsN)*360;
    %Step size for incoherent dots
    dXInCoh=DotSpeed*sind(RandDir)/Hertz;
    dYInCoh=DotSpeed*cosd(RandDir)/Hertz;




    for Frames=1:nFrames

        % for drawing fixation cross on every frame
        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);

        for j=1:Ndots
```

```
            % for drawing dots in respective frames
            if ColorFrames(j,Frames)==1
                Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColor,[],1);
            elseif ColorFrames(j,Frames)==2
                Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColorRev,[],1);
            end
        end
        Screen('Flip', MainWin);

        %for moving the dots
        if any(DispFrames(:)== Frames)

            %Moving coherent dots
            dots_X(CohIdx)=dots_X(CohIdx)+dXCoh;
            dots_Y(CohIdx)=dots_Y(CohIdx)+dYCoh;

            %Moving incoherent dots
            for Frames=1:numel(InCohIdx)
                InCohPixX(Frames)=InCohPixX(Frames)+dXInCoh(Frames);
                InCohPixY(Frames)=InCohPixY(Frames)+dYInCoh(Frames);
            end

            dots_X(InCohIdx)=InCohPixX;
            dots_Y(InCohIdx)=InCohPixY;


dots_X(dots_X>xRight)=rand(1,length(dots_X(dots_X>xRight)))*(xRight-
xLeft)+xLeft;

dots_X(dots_X<xLeft)=rand(1,length(dots_X(dots_X<xLeft)))*(xRight-
xLeft)+xLeft;
            dots_Y(dots_Y<yTop)=rand(1,length(dots_Y(dots_Y<yTop)))*(yBottom-
yTop)+yTop;

dots_Y(dots_Y>yBottom)=rand(1,length(dots_Y(dots_Y>yBottom)))*(yBottom-
yTop)+yTop;

            %limited lifetime dots
            dots_life = dots_life+1;
            deadDots = mod(dots_life,dots_lifetime)==0;

            dots_X(deadDots) = (rand(1,sum(deadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
            dots_Y(deadDots) = (rand(1,sum(deadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;
        end

    end

    %%%for keyboard responses:
    Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
    Screen('Flip', MainWin);
```

```
    keyIsDown = 0;
    StartTime = GetSecs;
    correct=0;
    RT=0;

    while 1
        [keyIsDown, timeSecs, keyCode] = KbCheck;
        FlushEvents('keyDown');
        if keyIsDown
            nKeys = sum(keyCode);
            if nKeys==1
                if
keyCode(UpArrow)||keyCode(DownArrow)||keyCode(LeftArrow)||keyCode(RightArrow)
                    RT = (timeSecs-StartTime);
                    keypressed=find(keyCode);
                    break;
                elseif keyCode(EscapeKey)
                    ShowCursor; Screen('CloseAll'); return
                end
                keyIsDown=0; keyCode=0;
            end
        end
    end



    if (keypressed==CorrKeys(3) && DotDirection == 180) ||
(keypressed==CorrKeys(4) && DotDirection == 0) || (keypressed==CorrKeys(1) &&
DotDirection == 270)|| (keypressed==CorrKeys(2) && DotDirection == 90)
        correct = 1; %phi
    elseif (keypressed==CorrKeys(4) && DotDirection == 180) ||
(keypressed==CorrKeys(3) && DotDirection == 0) || (keypressed==CorrKeys(2) &&
DotDirection == 270)|| (keypressed==CorrKeys(1) && DotDirection == 90)
        correct = 0; % reverse phi
    else
        correct=2; %guessing
    end


    % write the data
    results=[ConstStimN DotSpeed DotDirection StartTime timeSecs RT
keypressed TempStep DotCoherence correct];
    resultsAll=[resultsAll;results];

    WaitSecs(0.5);

end



resultsHead = {'nCS' 'DotSpeed' 'DotDirection' 'StartTime' 'timeSecs' 'RT'
'keypressed' 'TempStep' 'DotCoherence' 'correct'};
xlswrite(outputname,resultsHead,1,'A1');
```

```
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```

D) Reverse Phi motion – Motion Coherence experiment.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Reverse Phi motion
coherence experiment. Subjects have to response to the direction of
% motion of dots by pressing up,down, left, right arrow keys.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
```

```
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;


%%% RDK parameters
Ndots=500;
DotSize=5;
DotSpeed=480;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);
DotColor=White;

%dot lifetime
dots_lifetime=5;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%Temp interval
TempStep=1;

format shortG
%Positions of the dots
dots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
dots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;

%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];

%%%For Reverse phi
WhiteDotStart=1;
```

```
BlackDotStart=TempStep+WhiteDotStart;
BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
DispFrames=BlackDotStart-1:TempStep:nFrames;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Experimental instructions, wait for a spacebar response to start

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );

keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%VARIABLE STUDIED
ConstStimN = str2double(nCS);
DotCoherenceBasic=[0 0.05 0.075 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.7
1];
DotCoherenceRep=repmat(DotCoherenceBasic,1,ConstStimN);
DotCoherenceVect=DotCoherenceRep(randperm(length(DotCoherenceRep)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

resultsAll=[];
for Ntrialsi=1:length(DotCoherenceVect)
    DotCoherence=DotCoherenceVect(Ntrialsi);
    CohDotsN=ceil(DotCoherence*Ndots);
    InCohDotsN=Ndots-CohDotsN;

    Color=Shuffle([1 2]);
    ColorFramesBasic=zeros(1,nFrames);
    ColorFramesBasic(WhiteDotsFrames)=Color(1);
    ColorFramesBasic(BlackDotsFrames)=Color(2);

    lenColorFrames=length(ColorFramesBasic);
    ColorFrames=zeros(Ndots,lenColorFrames);
```

```
    for i=2:Ndots
        ColorFrames(1,:)=ColorFramesBasic;
        ColorFrames(i,:)=circshift(ColorFrames(i-1,:),lenColorFrames-1,2);
    end

    %for dot directions in any of the 4 directions
    DotDirectionN=Shuffle([0 90 180 270]);
    DotDirection=DotDirectionN(3);
    %stepsize
    dXCoh=DotSpeed*sind(DotDirection)/Hertz;
    dYCoh=DotSpeed*cosd(DotDirection)/Hertz;
    CohPix=dots_X(randperm(numel(dots_X),CohDotsN));
    [tf,loc]=ismember(dots_X,CohPix);
    idx=[1:length(dots_X)];
    idxC=idx(tf);
    CohIdx=idxC(loc(tf));
    %to find the incoherent dots pixels and index in X-axis and Y-axis
    [InCohPixX, InCohIdx]=setdiff(dots_X,CohPix);
    InCohPixY=dots_Y(InCohIdx);
    % random directions for incoherent dots
    RandDir=rand(1,InCohDotsN)*360;
    %Step size for incoherent dots
    dXInCoh=DotSpeed*sind(RandDir)/Hertz;
    dYInCoh=DotSpeed*cosd(RandDir)/Hertz;

    for Frames=1:nFrames

        % for drawing fixation cross on every frame
        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);

        % for drawing dots in respective frames
        for j=1:Ndots
            if ColorFrames(j,Frames)==1
                Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColor,[],1);
            elseif ColorFrames(j,Frames)==2
                Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize,
DotColorRev,[],1);
            end
        end



        Screen('Flip', MainWin);

        %for moving the dots
        if any(DispFrames(:)== Frames)
            %Moving coherent dots
            dots_X(CohIdx)=dots_X(CohIdx)+dXCoh;
            dots_Y(CohIdx)=dots_Y(CohIdx)+dYCoh;

            %Moving incoherent dots
            for Frames=1:numel(InCohIdx)
                InCohPixX(Frames)=InCohPixX(Frames)+dXInCoh(Frames);
                InCohPixY(Frames)=InCohPixY(Frames)+dYInCoh(Frames);
```

```
            end

            dots_X(InCohIdx)=InCohPixX;
            dots_Y(InCohIdx)=InCohPixY;


dots_X(dots_X>xRight)=rand(1,length(dots_X(dots_X>xRight)))*(xRight-
xLeft)+xLeft;

dots_X(dots_X<xLeft)=rand(1,length(dots_X(dots_X<xLeft)))*(xRight-
xLeft)+xLeft;
            dots_Y(dots_Y<yTop)=rand(1,length(dots_Y(dots_Y<yTop)))*(yBottom-
yTop)+yTop;

dots_Y(dots_Y>yBottom)=rand(1,length(dots_Y(dots_Y>yBottom)))*(yBottom-
yTop)+yTop;

            %limited lifetime dots
            dots_life = dots_life+1;
            deadDots = mod(dots_life,dots_lifetime)==0;

            dots_X(deadDots) = (rand(1,sum(deadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
            dots_Y(deadDots) = (rand(1,sum(deadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;
        end

    end

    %%%for keyboard responses:
    Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
    Screen('Flip', MainWin);


    keyIsDown = 0;
    StartTime = GetSecs;
    correct=0;
    RT=0;

    while 1
        [keyIsDown, timeSecs, keyCode] = KbCheck;
        FlushEvents('keyDown');
        if keyIsDown
            nKeys = sum(keyCode);
            if nKeys==1
                if
keyCode(UpArrow)||keyCode(DownArrow)||keyCode(LeftArrow)||keyCode(RightArrow)
                    RT = (timeSecs-StartTime);
                    keypressed=find(keyCode);
                    break;
                elseif keyCode(EscapeKey)
                    ShowCursor; Screen('CloseAll'); return
                end
                keyIsDown=0; keyCode=0;
            end
```

```
        end
    end


    if (keypressed==CorrKeys(4) && DotDirection == 180) ||
(keypressed==CorrKeys(3) && DotDirection == 0) || (keypressed==CorrKeys(2) &&
DotDirection == 270)|| (keypressed==CorrKeys(1) && DotDirection == 90)
        correct = 1; % reverse phi
    elseif (keypressed==CorrKeys(3) && DotDirection == 180) ||
(keypressed==CorrKeys(4) && DotDirection == 0) || (keypressed==CorrKeys(1) &&
DotDirection == 270)|| (keypressed==CorrKeys(2) && DotDirection == 90)
        correct = 0; % phi
    else
        correct=2; %guessing
    end

    % write the data
    results=[ConstStimN DotSpeed DotDirection StartTime timeSecs RT
keypressed TempStep DotCoherence correct];
    resultsAll=[resultsAll;results];

    WaitSecs(0.5);

end



resultsHead = {'nCS' 'DotSpeed' 'DotDirection' 'StartTime' 'timeSecs' 'RT'
'keypressed' 'TempStep' 'DotCoherence' 'correct'};
xlswrite(outputname,resultsHead,1,'A1');
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```

E) Phi motion – Transparent motion experiment.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Phi Transparent motion.
Subjects have to
% press left/ right arrow keys for left diagonal and right diagonal
directions of
% motion, respectively.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;  % clears all the window and workspace
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
```

```
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;


%%% RDK parameters
DotColor=White;
Ndots=500;
DotSize=5;
DotSpeed=240;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);


%dot lifetime
dots_lifetime=2;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%Positions of the dots for 'f'irst frame
Fdots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
Fdots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;

%For 's'econd frame of dots
Sdots_X=Fdots_X+5;
Sdots_Y=Fdots_Y+5;

%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];


WhiteDotStart=1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Experimental instructions

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );


keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
```

```
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ConstStimN = str2double(nCS);
TempStep=1;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HideCursor();
resultsAll=[];
BlackDotStart=TempStep+WhiteDotStart;
WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
DispFramesBasic=BlackDotStart-1:TempStep:nFrames;

DispFramesNext=DispFramesBasic-1;
ConcatDispFrames=[DispFramesBasic;DispFramesNext];
DispFrames=repmat(ConcatDispFrames,Ndots/2,1);

Color=[1 2];
ColorFramesBasic=zeros(1,nFrames);
ColorFramesBasic(WhiteDotsFrames)=Color(1);
ColorFramesBasic(BlackDotsFrames)=Color(1);
lenColorFrames=length(ColorFramesBasic);
ColorFrames=zeros(Ndots,lenColorFrames);
for i=2:Ndots
    ColorFrames(1,:)=ColorFramesBasic;
    if rem(i,2)==0
        ColorFrames(i,:)=2;
    else
        ColorFrames(i,:)=1;
    end
end

for Ntrialsi=1:ConstStimN
    FDotDirectionN=[135 225];
    SDotDirectionN=[315 45];
    FDotDirection=randsample(FDotDirectionN,1);
    indexFDotDir=FDotDirectionN==FDotDirection;
    SDotDirection=SDotDirectionN(indexFDotDir);
    %step size of displacement
    FdX=DotSpeed*sind(FDotDirection)/Hertz;

    FdY=DotSpeed*cosd(FDotDirection)/Hertz;
    SdX=DotSpeed*sind(SDotDirection)/Hertz;
    SdY=DotSpeed*cosd(SDotDirection)/Hertz;

    for Frames=1:nFrames
```

```
        % for drawing fixation cross on every frame
        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);
        for j=1:Ndots
            % for drawing dots in respective frames
            if ColorFrames(j,Frames)==1
                Screen('DrawDots',MainWin,[Fdots_X(j);Fdots_Y(j)], DotSize,
DotColor,[],1);
                Screen('DrawDots',MainWin,[Sdots_X(j);Sdots_Y(j)], DotSize,
DotColor,[],1);
            elseif ColorFrames(j,Frames)==2
                Screen('DrawDots',MainWin,[Fdots_X(j);Fdots_Y(j)], DotSize,
DotColorRev,[],1);
                Screen('DrawDots',MainWin,[Sdots_X(j);Sdots_Y(j)], DotSize,
DotColorRev,[],1);

            end
        end
        Screen('Flip', MainWin);

        if any(DispFrames(:)== Frames)
            Fdots_X= Fdots_X+(FdX);
            Fdots_Y= Fdots_Y+(FdY);

            % to prevent dots from moving outside the aperture.
            Fdots_X(Fdots_X>xRight)=Fdots_X(Fdots_X>xRight)-Aperture_r*2;
            Fdots_X(Fdots_X<xLeft)=Fdots_X(Fdots_X<xLeft)+Aperture_r*2;
            Fdots_Y(Fdots_Y<yTop)=Fdots_Y(Fdots_Y<yTop)+Aperture_r*2;
            Fdots_Y(Fdots_Y>yBottom)=Fdots_Y(Fdots_Y>yBottom)-Aperture_r*2;
            %

            %%limited lifetime dots
            dots_life = dots_life+1;
            FdeadDots = mod(dots_life,dots_lifetime)==0;

            Fdots_X(FdeadDots) = (rand(1,sum(FdeadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
            Fdots_Y(FdeadDots) = (rand(1,sum(FdeadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;

            % for displacements in Second frame of dots
            Sdots_X= Sdots_X+(SdX);
            Sdots_Y= Sdots_Y+(SdY);
            %                 to prevent dots from moving outside the
aperture.
            Sdots_X(Sdots_X>xRight)=Sdots_X(Sdots_X>xRight)-Aperture_r*2;
            Sdots_X(Sdots_X<xLeft)=Sdots_X(Sdots_X<xLeft)+Aperture_r*2;
            Sdots_Y(Sdots_Y<yTop)=Sdots_Y(Sdots_Y<yTop)+Aperture_r*2;
            Sdots_Y(Sdots_Y>yBottom)=Sdots_Y(Sdots_Y>yBottom)-Aperture_r*2;

            %
            %limited lifetime dots
            dots_life = dots_life+1;
            SdeadDots = mod(dots_life,dots_lifetime)==0;
            %
```

```
            Sdots_X(SdeadDots) = (rand(1,sum(SdeadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
            Sdots_Y(SdeadDots) = (rand(1,sum(SdeadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;

        end

    end

    %%%for keyboard responses:
    Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
    Screen('Flip', MainWin);


    keyIsDown = 0;
    StartTime = GetSecs;
    correct=0;
    RT=0;

    while 1
        [keyIsDown, timeSecs, keyCode] = KbCheck;
        FlushEvents('keyDown');
        if keyIsDown
            nKeys = sum(keyCode);
            if nKeys==1
                if
keyCode(UpArrow)||keyCode(DownArrow)||keyCode(LeftArrow)||keyCode(RightArrow)
                    RT = (timeSecs-StartTime);
                    keypressed=find(keyCode);
                    break;
                elseif keyCode(EscapeKey)
                    ShowCursor; Screen('CloseAll'); return
                end
                keyIsDown=0; keyCode=0;
            end
        end
    end

    if (keypressed==CorrKeys(4) && FDotDirection == 90) ||
(keypressed==CorrKeys(3) && FDotDirection == 0) || (keypressed==CorrKeys(2)
&& FDotDirection == 135)|| (keypressed==CorrKeys(1) && FDotDirection == 225)
        correct = "TM"; % TM
    elseif (keypressed==CorrKeys(4) && FDotDirection == 0) ||
(keypressed==CorrKeys(3) && FDotDirection == 90) || (keypressed==CorrKeys(2)
&& FDotDirection == 225)|| (keypressed==CorrKeys(1) && FDotDirection == 135)
        correct = "orthogonal"; % Orthogonal
    else
        correct=2; %guessing
    end

    keypress=convertCharsToStrings(KbName(keypressed));

    %     write the data
    results=[ConstStimN DotSpeed TempStep FdX FdY FDotDirection SDotDirection
StartTime timeSecs RT keypress correct];
```

```
    resultsAll=[resultsAll;results];


    WaitSecs(0.5);

end

resultsHead = {'ConstStimN' 'DotSpeed' 'TempStep' 'FdX' 'FdY' 'FDotDirection'
'SDotDirection' 'StartTime' 'timeSecs' 'RT' 'keypress' 'correct'};
xlswrite(outputname,resultsHead,1,'A1');
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```

F) Reverse Phi motion – Transparent motion experiment.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Reverse Phi Transparent
motion. Subjects have to
% press left/ right arrow keys for left diagonal and right diagonal
directions of
% motion, respectively.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
```

```
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;


%%% RDK parameters
DotColor=White;
Ndots=500;
DotSize=5;
DotSpeed=240;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);


%dot lifetime
dots_lifetime=2;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%Positions of the dots for 'f'irst frame
Fdots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
Fdots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;
```

```
%For 's'econd frame of dots
Sdots_X=Fdots_X+5;
Sdots_Y=Fdots_Y+5;

%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];


WhiteDotStart=1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Experimental instructions

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );



keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ConstStimN = str2double(nCS);
TempStep=1;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HideCursor();
resultsAll=[];
BlackDotStart=TempStep+WhiteDotStart;
WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
```

```
DispFramesBasic=BlackDotStart-1:TempStep:nFrames;

DispFramesNext=DispFramesBasic-1;
ConcatDispFrames=[DispFramesBasic;DispFramesNext];
DispFrames=repmat(ConcatDispFrames,Ndots/2,1);

Color=Shuffle([1 2]);
ColorFramesBasic=zeros(1,nFrames);
ColorFramesBasic(WhiteDotsFrames)=Color(1);
ColorFramesBasic(BlackDotsFrames)=Color(2);

lenColorFrames=length(ColorFramesBasic);
ColorFrames=zeros(Ndots,lenColorFrames);
for i=2:Ndots
    ColorFrames(1,:)=ColorFramesBasic;
    ColorFrames(i,:)=circshift(ColorFrames(i-1,:),lenColorFrames-1,2);
end


for Ntrialsi=1:ConstStimN
    %for dot directions in any of the 4 directions
    FDotDirectionN=[135 225];
    SDotDirectionN=[315 45];
    FDotDirection=randsample(FDotDirectionN,1);
    indexFDotDir=FDotDirectionN==FDotDirection;
    SDotDirection=SDotDirectionN(indexFDotDir);
    FdX=DotSpeed*sind(FDotDirection)/Hertz;

    FdY=DotSpeed*cosd(FDotDirection)/Hertz;

    SdX=DotSpeed*sind(SDotDirection)/Hertz;

    SdY=DotSpeed*cosd(SDotDirection)/Hertz;

    for Frames=1:nFrames

        % for drawing fixation cross on every frame
        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);

        % for drawing dots in respective frames
        for j=1:Ndots
            % for drawing dots in respective frames
            if ColorFrames(j,Frames)==1
                Screen('DrawDots',MainWin,[Fdots_X(j);Fdots_Y(j)], DotSize,
DotColor,[],1);
                Screen('DrawDots',MainWin,[Sdots_X(j);Sdots_Y(j)], DotSize,
DotColor,[],1);
            elseif ColorFrames(j,Frames)==2
                Screen('DrawDots',MainWin,[Fdots_X(j);Fdots_Y(j)], DotSize,
DotColorRev,[],1);
                Screen('DrawDots',MainWin,[Sdots_X(j);Sdots_Y(j)], DotSize,
DotColorRev,[],1);
            end
        end
```

```
        Screen('Flip', MainWin);

        if any(DispFrames(:)== Frames)
            Fdots_X= Fdots_X+(FdX);
            Fdots_Y= Fdots_Y+(FdY);
            % %                 to prevent dots from moving outside the
aperture.
            Fdots_X(Fdots_X>xRight)=Fdots_X(Fdots_X>xRight)-Aperture_r*2;
            Fdots_X(Fdots_X<xLeft)=Fdots_X(Fdots_X<xLeft)+Aperture_r*2;
            Fdots_Y(Fdots_Y<yTop)=Fdots_Y(Fdots_Y<yTop)+Aperture_r*2;
            Fdots_Y(Fdots_Y>yBottom)=Fdots_Y(Fdots_Y>yBottom)-Aperture_r*2;
            %

            %%limited lifetime dots
            dots_life = dots_life+1;
            FdeadDots = mod(dots_life,dots_lifetime)==0;

            Fdots_X(FdeadDots) = (rand(1,sum(FdeadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
            Fdots_Y(FdeadDots) = (rand(1,sum(FdeadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;

            % for displacements in Second frame of dots
            Sdots_X= Sdots_X+(SdX);
            Sdots_Y= Sdots_Y+(SdY);
            %
            %                 to prevent dots from moving outside the
aperture.
            Sdots_X(Sdots_X>xRight)=Sdots_X(Sdots_X>xRight)-Aperture_r*2;
            Sdots_X(Sdots_X<xLeft)=Sdots_X(Sdots_X<xLeft)+Aperture_r*2;
            Sdots_Y(Sdots_Y<yTop)=Sdots_Y(Sdots_Y<yTop)+Aperture_r*2;
            Sdots_Y(Sdots_Y>yBottom)=Sdots_Y(Sdots_Y>yBottom)-Aperture_r*2;
            %
            %
            %limited lifetime dots
            dots_life = dots_life+1;
            SdeadDots = mod(dots_life,dots_lifetime)==0;
            %
            Sdots_X(SdeadDots) = (rand(1,sum(SdeadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
            Sdots_Y(SdeadDots) = (rand(1,sum(SdeadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;

        end
        %
    end


    %%%for keyboard responses:
    Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
    Screen('Flip', MainWin);


    keyIsDown = 0;
    StartTime = GetSecs;
```

```
    correct=0;
    RT=0;

    while 1
        [keyIsDown, timeSecs, keyCode] = KbCheck;
        FlushEvents('keyDown');
        if keyIsDown
            nKeys = sum(keyCode);
            if nKeys==1
                if
keyCode(UpArrow)||keyCode(DownArrow)||keyCode(LeftArrow)||keyCode(RightArrow)
                    RT = (timeSecs-StartTime);
                    keypressed=find(keyCode);
                    break;
                elseif keyCode(EscapeKey)
                    ShowCursor; Screen('CloseAll'); return
                end
                keyIsDown=0; keyCode=0;
            end
        end
    end


    if (keypressed==CorrKeys(4) && FDotDirection == 90) ||
(keypressed==CorrKeys(3) && FDotDirection == 0) || (keypressed==CorrKeys(2)
&& FDotDirection == 135)|| (keypressed==CorrKeys(1) && FDotDirection == 225)
        correct = "TM"; % TM
    elseif (keypressed==CorrKeys(4) && FDotDirection == 0) ||
(keypressed==CorrKeys(3) && FDotDirection == 90) || (keypressed==CorrKeys(2)
&& FDotDirection == 225)|| (keypressed==CorrKeys(1) && FDotDirection == 135)
        correct = "orthogonal"; % Orthogonal
    else
        correct=2; %guessing
    end

    keypress=convertCharsToStrings(KbName(keypressed));

    % write the data
    results=[ConstStimN DotSpeed TempStep FdX FdY FDotDirection SDotDirection
StartTime timeSecs RT keypress correct];
    resultsAll=[resultsAll;results];


    WaitSecs(0.5);

end

resultsHead = {'ConstStimN' 'DotSpeed' 'TempStep' 'FdX' 'FdY' 'FDotDirection'
'SDotDirection' 'StartTime' 'timeSecs' 'RT' 'keypress' 'correct'};
xlswrite(outputname,resultsHead,1,'A1');
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```

G) Nulling experiment.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Nulling experiment.
Subjects have to
% press left/ right arrow keys to respond to the direction of
% motion.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
CorrKeys=[LeftArrow RightArrow UpArrow DownArrow];

%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;

%%% RDK parameters
DotColor=White;
DotColorRev=Black;
Ndots=250;
DotSize=5;
DotSpeed=700;
DotDur=1;
nFrames=ceil(Hertz*DotDur);



%dot lifetime
dots_lifetime=3;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];



WhiteDotStart=1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Experimental instructions,

Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,('Press spacebar to start the experiment.')
,xCenter-200,yCenter,White);
Screen('Flip',MainWin );

keyIsDown=0;
while 1
```

```
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ConstStimN = str2double(nCS);
TempStep=1;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HideCursor();
resultsAll=[];


BlackDotStart=TempStep+WhiteDotStart;
BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;

DispFramesBasic=BlackDotStart-1:TempStep:nFrames;
DispFramesNext=DispFramesBasic-1;
ConcatDispFrames=[DispFramesBasic;DispFramesNext];
DispFrames=repmat(ConcatDispFrames,Ndots/2,1);

Color=Shuffle([1 2]);
ColorFramesBasicRP=zeros(1,nFrames);
ColorFramesBasicRP(WhiteDotsFrames)=Color(1);
ColorFramesBasicRP(BlackDotsFrames)=Color(2);

lenColorFramesRP=length(ColorFramesBasicRP);
ColorFramesRP=zeros(Ndots,lenColorFramesRP);
for i=2:Ndots
    ColorFramesRP(1,:)=ColorFramesBasicRP;
    ColorFramesRP(i,:)=circshift(ColorFramesRP(i-1,:),lenColorFramesRP-1,2);
end

%% For Phi
ColorFramesBasicPhi=zeros(1,nFrames);
ColorFramesBasicPhi(WhiteDotsFrames)=Color(1);
ColorFramesBasicPhi(BlackDotsFrames)=Color(1);
lenColorFramesPhi=length(ColorFramesBasicPhi);
```

```
ColorFramesPhi=zeros(Ndots,lenColorFramesPhi);
for i=2:Ndots
    ColorFramesPhi(1,:)=ColorFramesBasicPhi;
    if rem(i,2)==0
        ColorFramesPhi(i,:)=2;
    else
        ColorFramesPhi(i,:)=1;
    end
end

%%
for Ntrialsi=1:ConstStimN

    PhiCoherence=[0 0.05 0.1 0.3 0.6 0.9 1];

    for PhiCoherencei=1:length(PhiCoherence)

        %Positions of the dots for 'f'irst frame
        Fdots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
        Fdots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;

        %For 's'econd frame of dots
        Sdots_X=Fdots_X+5;
        Sdots_Y=Fdots_Y+5;

        % determine number of dots in second frame i.e.Phi
        SdotsN=Ndots*PhiCoherence(PhiCoherencei);
        SdotsNAct=round((Ndots-SdotsN)/2);
        SStart=SdotsNAct+1;
        SEnd=Ndots-SdotsNAct;
        Sdots_X= Sdots_X(SStart:SEnd);
        Sdots_Y=Sdots_Y(SStart:SEnd);

        %for dot directions in any of the 4 directions
        FDotDirectionN=Shuffle([90 270]);

        FDotDirection=FDotDirectionN(1);

        SDotDirection=FDotDirection;




        %step size of RP (first component)
        FdX=DotSpeed*sind(FDotDirection)/Hertz;
        FdY=DotSpeed*cosd(FDotDirection)/Hertz;
        SdX=DotSpeed*sind(SDotDirection)/Hertz;
        SdY=DotSpeed*cosd(SDotDirection)/Hertz;
        for Frames=1:nFrames

            % for drawing fixation cross on every frame
            Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);
            % for drawing dots in respective frames
```

```
      for j=1:Ndots
        %        for drawing dots in respective frames
        if ColorFramesRP(j,Frames)==1
          Screen('DrawDots',MainWin,[Fdots_X(j);Fdots_Y(j)],
DotSize, DotColor,[],1);
        elseif ColorFramesRP(j,Frames)==2
          Screen('DrawDots',MainWin,[Fdots_X(j);Fdots_Y(j)],
DotSize, DotColorRev,[],1);
        end
        if j<length(Sdots_X)+1
          if ColorFramesPhi(j,Frames)==1
            Screen('DrawDots',MainWin,[Sdots_X(j);Sdots_Y(j)],
DotSize, DotColor,[],1);
          elseif ColorFramesPhi(j,Frames)==2
            Screen('DrawDots',MainWin,[Sdots_X(j);Sdots_Y(j)],
DotSize, DotColorRev,[],1);
          end
        end

      end

      Screen('Flip', MainWin);
      %displacements for first component - reverse phi
      if any(DispFrames(:)== Frames)
        Fdots_X= Fdots_X+(FdX);
        Fdots_Y= Fdots_Y+(FdY);

        %%        to prevent dots from moving outside the
aperture.
        Fdots_X(Fdots_X>xRight)=Fdots_X(Fdots_X>xRight)-Aperture_r*2;
        Fdots_X(Fdots_X<xLeft)=Fdots_X(Fdots_X<xLeft)+Aperture_r*2;
        Fdots_Y(Fdots_Y<yTop)=Fdots_Y(Fdots_Y<yTop)+Aperture_r*2;
        Fdots_Y(Fdots_Y>yBottom)=Fdots_Y(Fdots_Y>yBottom)-
Aperture_r*2;
        %
        Sdots_X= Sdots_X+(SdX);
        Sdots_Y= Sdots_Y+(SdY);

Sdots_X(Sdots_X>xRight)=rand(1,length(Sdots_X(Sdots_X>xRight)))*(xRight-
xLeft)+xLeft;

Sdots_X(Sdots_X<xLeft)=rand(1,length(Sdots_X(Sdots_X<xLeft)))*(xRight-
xLeft)+xLeft;

Sdots_Y(Sdots_Y<yTop)=rand(1,length(Sdots_Y(Sdots_Y<yTop)))*(yBottom-
yTop)+yTop;

Sdots_Y(Sdots_Y>yBottom)=rand(1,length(Sdots_Y(Sdots_Y>yBottom)))*(yBottom-
yTop)+yTop;

        %%limited lifetime dots
        dots_life = ceil(rand(1,Ndots)*dots_lifetime);
        dots_life = dots_life+1;
        FdeadDots = mod(dots_life,dots_lifetime)==0;
```

```
                Fdots_X(FdeadDots) = (rand(1,sum(FdeadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
                Fdots_Y(FdeadDots) = (rand(1,sum(FdeadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;

                %limited lifetime dots
                dots_life = ceil(rand(1,length(Sdots_X))*dots_lifetime);
                dots_life = dots_life+1;
                deadDots = mod(dots_life,dots_lifetime)==0;

                Sdots_X(deadDots) = (rand(1,sum(deadDots))-.5)*(xRight-
xLeft)+xLeft+Aperture_r;
                Sdots_Y(deadDots) = (rand(1,sum(deadDots))-.5)*(yBottom-
yTop)+yTop+Aperture_r;
            end
        end
        %%
        %%%for keyboard responses:
        Screen('DrawLines', MainWin, Fix_XY, 4, [0 255 0],[xCenter,
yCenter],2);
        Screen('Flip', MainWin);


        keyIsDown = 0;
        StartTime = GetSecs;
        correct=0;
        RT=0;

        while 1
            [keyIsDown, timeSecs, keyCode] = KbCheck;
            FlushEvents('keyDown');
            if keyIsDown
                nKeys = sum(keyCode);
                if nKeys==1
                    if
keyCode(LeftArrow)||keyCode(RightArrow)||keyCode(DownArrow)
                        RT = (timeSecs-StartTime);
                        keypressed=find(keyCode);
                        break;
                    elseif keyCode(EscapeKey)
                        ShowCursor; Screen('CloseAll'); return
                    end
                    keyIsDown=0; keyCode=0;
                end
            end
        end


        if ((keypressed==CorrKeys(1) && FDotDirection == 270) ||
(keypressed==CorrKeys(2) && FDotDirection == 90))
            correct = "Phi"; % TM
        elseif ((keypressed==CorrKeys(1) && FDotDirection == 90) ||
(keypressed==CorrKeys(2) && FDotDirection == 270))
            correct = "RP"; % RP
```

```
        elseif ((keypressed==CorrKeys(3) && FDotDirection == 90) ||
(keypressed==CorrKeys(3) && FDotDirection == 270))
            correct="TM"; %guessing
        end

        keypress=convertCharsToStrings(KbName(keypressed));
        PhiCoh=PhiCoherence(PhiCoherencei);
        %to recheck the numbers of Sdots
        SdotsX=length(Sdots_X);
        SdotsY=length(Sdots_Y);

        % write the data
        results=[ConstStimN DotSpeed FdX FdY PhiCoh SdotsN SdotsX SdotsY
FDotDirection SDotDirection StartTime timeSecs RT keypress correct];
        resultsAll=[resultsAll;results];



        WaitSecs(0.5);

    end
end




resultsHead = {'ConstStimN' 'DotSpeed' 'FdX' 'FdY' 'PhiCoh' 'SdotsN' 'SdotsX'
'SdotsY' 'FDotDirection' 'SDotDirection' 'StartTime' 'timeSecs' 'RT'
'keypress' 'correct'}; % all data that I need from the iteration
xlswrite(outputname,resultsHead,1,'A1');
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```

H) Speed discrimination experiment.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% This program displays random dot kinematograms - Speed discrimination
experiment. Subjects have to respond whether the first
% or the second interval contained the fastest stimulus by pressing 1 or 2
number key.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
close all;
format shortG

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Login PROMPT and OPEN FILE for writing data out
prompt = {'Outputfile','Subject''s name:', 'Subject''s number:', 'age',
'gender','Num of ConstStimuli'};
defaults = {'RDK_Phi_Center', 'A','1', '18', 'F', '5'};
answer = inputdlg(prompt, 'RDK_Phi_Center', 2, defaults);
[output, subname, subid, subage, gender, nCS] = deal(answer{:});
outputname = [output '_' subname '_' subid '_' subage gender '.xls'];


if exist(outputname)==2
    fileproblem = input('That file already exists! Append a .x (1), overwrite
(2), or break (3/default)?');
    if isempty(fileproblem) || fileproblem==3
        return;
    elseif fileproblem==1
        outputname = [outputname '.x'];
    end
end

CurrentDir='C:\Users\mkp\Desktop';
cd(CurrentDir);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% EXPERIMENTAL PARAMETERS

%%% Available keys to press
KbName('UnifyKeyNames');
EscapeKey=KbName('Escape');
SpaceKey=KbName('Space');
UpArrow=KbName('UpArrow');
DownArrow = KbName('DownArrow');
LeftArrow = KbName('LeftArrow');
RightArrow = KbName('RightArrow');
First=KbName('1');
Second=KbName('2');
Same=KbName('3');
CorrKeys=[First Second Same];
```

```
%%% Luminance levels in gray levels
Grey=[127 127 127]; White=[255 255 255]; Black=[0 0 0];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SCREEN PARAMETERS
Screen('Preference', 'SkipSyncTests', 1);
NoOfScreens=Screen('Screens');
ScreenNum=max(NoOfScreens);
[MainWin, Winrect]=Screen('OpenWindow',ScreenNum,Grey);
[screenXpixels, screenYpixels] = Screen('WindowSize', ScreenNum);
[xCenter, yCenter] = RectCenter(Winrect);
ifi = Screen('GetFlipInterval', MainWin);
Hertz=FrameRate(MainWin);
Screen('BlendFunction', MainWin, GL_SRC_ALPHA, GL_ONE_MINUS_SRC_ALPHA);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%Aperture parameters
Aperture_r = 200;
Square=[(xCenter-Aperture_r) (yCenter-Aperture_r) (xCenter+Aperture_r)
(yCenter+Aperture_r)];
xLeft=xCenter-Aperture_r; xRight=xCenter+Aperture_r; yTop=yCenter-Aperture_r;
yBottom=yCenter+Aperture_r;

%%% RDK parameters
DotColor=White;
DotColorRev=Black;
Ndots=500;
DotSize=5;
DotDur=0.5;
nFrames=ceil(Hertz*DotDur);
TempStep=1;

%dot lifetime
dots_lifetime=2;
dots_life = ceil(rand(1,Ndots)*dots_lifetime);

%Positions of the dots
dots_X=rand(1,Ndots)*(xRight-xLeft)+xLeft;
dots_Y=rand(1,Ndots)*(yBottom-yTop)+yTop;


%%%Fixation Cross parameters
Fix_length=10;
Fix_X=[-Fix_length Fix_length 0 0];
Fix_Y=[0 0 -Fix_length Fix_length];
Fix_XY=[Fix_X; Fix_Y];


WhiteDotStart=1;
ConstStimN = str2double(nCS);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%   Experimental instructions
```

```
Screen('FillRect', MainWin ,Grey);
Screen('TextSize', MainWin, 24);
Screen('DrawText',MainWin,'Press spacebar to start the experiment.' ,xCenter-
200,yCenter,White);
Screen('Flip',MainWin );

keyIsDown=0;
while 1
    [keyIsDown, timeSecs, keyCode] = KbCheck;
    if keyIsDown
        if keyCode(SpaceKey)
            break ;
        elseif keyCode(EscapeKey)
            ShowCursor;
            Screen('CloseAll');
            return;
        end
    end
end

Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter, yCenter],2);
Screen('Flip',MainWin );
WaitSecs(0.3);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

HideCursor();
resultsAll=[];
for Ntrials=1:ConstStimN
    StdDotSpeed= [976]; % change it to [712 976 1480] on next runs. For 712,
delete 0.5 from test speed

    for StdSpeedi=1:length(StdDotSpeed)
        TestSpeed=[0.5 0.7 1 1.2 1.45]; % in percentage [60 80 100 120 150
200], for 712, delete 0.5, 0.5 0.7 1 1.2 1.45
        TestSpeedAct=StdDotSpeed(StdSpeedi)*TestSpeed;
        TestDotSpeed=Shuffle(TestSpeedAct);

        for TestSpeedi=1:length(TestDotSpeed)
            Conditions=Shuffle([11 12 22 21]);% 4 combinations -  P-P (1-1),
P-RP (1-2),  RP-RP (2-2), RP-P (2-1); 1 means phi, 2 means reverse phi. 11 12
22 21
            for  Conditionsi=1:4
                ConditionNow= num2str(Conditions(Conditionsi));
                I1 = str2double(ConditionNow(1));
                I2=str2double(ConditionNow(2));


                if I1==1 % odd number; so draw phi
                    %Interval 1
                    WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
                    BlackDotStart=TempStep+WhiteDotStart;
                    BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
                    DispFrames=BlackDotStart-1:TempStep:nFrames;
                    Color=[1 2];
```

```
                    ColorFramesBasic=zeros(1,nFrames);
                    ColorFramesBasic(WhiteDotsFrames)=Color(1);
                    ColorFramesBasic(BlackDotsFrames)=Color(1);
                    lenColorFrames=length(ColorFramesBasic);
                    ColorFrames=zeros(Ndots,lenColorFrames);
                    for i=2:Ndots
                        ColorFrames(1,:)=ColorFramesBasic;
                        if rem(i,2)==0
                            ColorFrames(i,:)=2;
                        else
                            ColorFrames(i,:)=1;
                        end
                    end
                    DotDirectionN=Shuffle([0 90 180 270]);
                    DotDirectionI1=DotDirectionN(1);

                    %step size of displacement
                    SdX=StdDotSpeed(StdSpeedi)*sind(DotDirectionI1)/Hertz;
                    SdY=StdDotSpeed(StdSpeedi)*cosd(DotDirectionI1)/Hertz;
                    for Frames=1:nFrames
                        % for drawing fixation cross on every frame
                        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0
0],[xCenter, yCenter],2);
                        % for drawing dots in respective frames
                        for j=1:Ndots
                            % for drawing dots in respective frames
                            if ColorFrames(j,Frames)==1

Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize, DotColor,[],1);
                            elseif ColorFrames(j,Frames)==2

Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize, DotColorRev,[],1);
                            end
                        end
                        Screen('Flip', MainWin);
                        %Move dots
                        if any(DispFrames(:)== Frames)
                            dots_X= dots_X+(SdX);
                            dots_Y= dots_Y+(SdY);
                            % to prevent dots from moving outside the
aperture.
                            dots_X(dots_X>xRight)=dots_X(dots_X>xRight)-
Aperture_r*2;

dots_X(dots_X<xLeft)=dots_X(dots_X<xLeft)+Aperture_r*2;

dots_Y(dots_Y<yTop)=dots_Y(dots_Y<yTop)+Aperture_r*2;
                            dots_Y(dots_Y>yBottom)=dots_Y(dots_Y>yBottom)-
Aperture_r*2;


                            %%limited lifetime dots
                            dots_life = dots_life+1;
                            deadDots = mod(dots_life,dots_lifetime)==0;
```

```
                            dots_X(deadDots) = (rand(1,sum(deadDots))-
.5)*(xRight-xLeft)+xLeft+Aperture_r;
                            dots_Y(deadDots) = (rand(1,sum(deadDots))-
.5)*(yBottom-yTop)+yTop+Aperture_r;


                        end
                    end

                elseif I1==2 % it is an even number draw reverse phi
                    WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
                    BlackDotStart=TempStep+WhiteDotStart;
                    BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
                    DispFrames=BlackDotStart-1:TempStep:nFrames;
                    Color=[1 2];
                    ColorFrames=zeros(1,nFrames);
                    ColorFrames(WhiteDotsFrames)=Color(1);
                    ColorFrames(BlackDotsFrames)=Color(2);

                    DotDirectionN=Shuffle([0 90 180 270]);
                    DotDirectionI1=DotDirectionN(1);
                    %step size of displacement
                    SdX=StdDotSpeed(StdSpeedi)*sind(DotDirectionI1)/Hertz;
                    SdY=StdDotSpeed(StdSpeedi)*cosd(DotDirectionI1)/Hertz;
                    for Frames=1:nFrames
                        % for drawing fixation cross on every frame
                        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0
0],[xCenter, yCenter],2);

                        % for drawing dots in respective frames
                        if ColorFrames(Frames)==1
                            Screen('DrawDots',MainWin,[dots_X;dots_Y],
DotSize, DotColor,[],1);
                        elseif ColorFrames(Frames)==2
                            Screen('DrawDots',MainWin,[dots_X;dots_Y],
DotSize, DotColorRev,[],1);
                        end
                        Screen('Flip', MainWin);
                        %Move dots
                        if any(DispFrames(:)== Frames)
                            dots_X= dots_X+(SdX);
                            dots_Y= dots_Y+(SdY);
                            % to prevent dots from moving outside the
aperture.
                            dots_X(dots_X>xRight)=dots_X(dots_X>xRight)-
Aperture_r*2;

dots_X(dots_X<xLeft)=dots_X(dots_X<xLeft)+Aperture_r*2;

dots_Y(dots_Y<yTop)=dots_Y(dots_Y<yTop)+Aperture_r*2;
                            dots_Y(dots_Y>yBottom)=dots_Y(dots_Y>yBottom)-
Aperture_r*2;


                            %%limited lifetime dots
```

```
                            dots_life = dots_life+1;
                            deadDots = mod(dots_life,dots_lifetime)==0;

                            dots_X(deadDots) = (rand(1,sum(deadDots))-
.5)*(xRight-xLeft)+xLeft+Aperture_r;
                            dots_Y(deadDots) = (rand(1,sum(deadDots))-
.5)*(yBottom-yTop)+yTop+Aperture_r;


                        end
                    end
                end
                %%
                % For ISI
                Screen('DrawLines', MainWin, Fix_XY, 4, [255 0 0],[xCenter,
yCenter],2);
                Screen('Flip', MainWin);
                ISI = 0.2;
                WaitSecs(ISI);

                %%
                %Interval 2:
                if I2==2 % if correct, i.e., odd number, then draw reverse
phi because Std would have been phi
                    WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
                    BlackDotStart=TempStep+WhiteDotStart;
                    BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
                    DispFrames=BlackDotStart-1:TempStep:nFrames;
                    Color=[1 2];
                    ColorFrames=zeros(1,nFrames);
                    ColorFrames(WhiteDotsFrames)=Color(1);
                    ColorFrames(BlackDotsFrames)=Color(2);

                    if str2double(ConditionNow)== 11 ||
str2double(ConditionNow)== 22
                        DotDirectionI2=DotDirectionI1;
                    else
                        if DotDirectionI1<95
                            DotDirectionI2=DotDirectionI1+180;
                        else
                            DotDirectionI2=DotDirectionI1-180;
                        end
                    end

                    %step size of displacement
                    TdX=TestDotSpeed(TestSpeedi)*sind(DotDirectionI2)/Hertz;
                    TdY=TestDotSpeed(TestSpeedi)*cosd(DotDirectionI2)/Hertz;
                    for Frames=1:nFrames
                        % for drawing fixation cross on every frame
                        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0
0],[xCenter, yCenter],2);
                        % for drawing dots in respective frames
                        if ColorFrames(Frames)==1
                            Screen('DrawDots',MainWin,[dots_X;dots_Y],
DotSize, DotColor,[],1);
                        elseif ColorFrames(Frames)==2
```

```
                            Screen('DrawDots',MainWin,[dots_X;dots_Y],
DotSize, DotColorRev,[],1);
                        end
                        Screen('Flip', MainWin);
                        %Move dots
                        if any(DispFrames(:)== Frames)
                            dots_X= dots_X+(TdX);
                            dots_Y= dots_Y+(TdY);
                            % to prevent dots from moving outside the
aperture.
                            dots_X(dots_X>xRight)=dots_X(dots_X>xRight)-
Aperture_r*2;

dots_X(dots_X<xLeft)=dots_X(dots_X<xLeft)+Aperture_r*2;

dots_Y(dots_Y<yTop)=dots_Y(dots_Y<yTop)+Aperture_r*2;
                            dots_Y(dots_Y>yBottom)=dots_Y(dots_Y>yBottom)-
Aperture_r*2;



                            %%limited lifetime dots
                            dots_life = dots_life+1;
                            deadDots = mod(dots_life,dots_lifetime)==0;

                            dots_X(deadDots) = (rand(1,sum(deadDots))-
.5)*(xRight-xLeft)+xLeft+Aperture_r;
                            dots_Y(deadDots) = (rand(1,sum(deadDots))-
.5)*(yBottom-yTop)+yTop+Aperture_r;

                        end
                    end

                elseif I2==1 % it is even number draw phi
                    WhiteDotsFrames=WhiteDotStart:TempStep:nFrames;
                    BlackDotStart=TempStep+WhiteDotStart;
                    BlackDotsFrames=BlackDotStart:TempStep*2:nFrames;
                    DispFrames=BlackDotStart-1:TempStep:nFrames;
                    Color=[1 2];
                    ColorFramesBasic=zeros(1,nFrames);
                    ColorFramesBasic(WhiteDotsFrames)=Color(1);
                    ColorFramesBasic(BlackDotsFrames)=Color(1);
                    lenColorFrames=length(ColorFramesBasic);
                    ColorFrames=zeros(Ndots,lenColorFrames);
                    for i=2:Ndots
                        ColorFrames(1,:)=ColorFramesBasic;
                        if rem(i,2)==0
                            ColorFrames(i,:)=2;
                        else
                            ColorFrames(i,:)=1;
                        end
                    end

                    if str2double(ConditionNow)== 11 ||
str2double(ConditionNow)== 22
                        DotDirectionI2=DotDirectionI1;
                    else
```

```
                        if DotDirectionI1<95
                            DotDirectionI2=DotDirectionI1+180;
                        else
                            DotDirectionI2=DotDirectionI1-180;
                        end
                    end

                    %step size of displacement
                    TdX=TestDotSpeed(TestSpeedi)*sind(DotDirectionI2)/Hertz;
                    TdY=TestDotSpeed(TestSpeedi)*cosd(DotDirectionI2)/Hertz;
                    for Frames=1:nFrames
                        % for drawing fixation cross on every frame
                        Screen('DrawLines', MainWin, Fix_XY, 4, [255 0
0],[xCenter, yCenter],2);
                        % for drawing dots in respective frames
                        for j=1:Ndots
                            % for drawing dots in respective frames
                            if ColorFrames(j,Frames)==1

Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize, DotColor,[],1);
                            elseif ColorFrames(j,Frames)==2

Screen('DrawDots',MainWin,[dots_X(j);dots_Y(j)], DotSize, DotColorRev,[],1);
                            end
                        end
                        Screen('Flip', MainWin);

                        %Move dots
                        if any(DispFrames(:)== Frames)
                            dots_X= dots_X+(TdX);
                            dots_Y= dots_Y+(TdY);
                            % to prevent dots from moving outside the
aperture.
                            dots_X(dots_X>xRight)=dots_X(dots_X>xRight)-
Aperture_r*2;

dots_X(dots_X<xLeft)=dots_X(dots_X<xLeft)+Aperture_r*2;

dots_Y(dots_Y<yTop)=dots_Y(dots_Y<yTop)+Aperture_r*2;
                            dots_Y(dots_Y>yBottom)=dots_Y(dots_Y>yBottom)-
Aperture_r*2;



                            %%limited lifetime dots
                            dots_life = dots_life+1;
                            deadDots = mod(dots_life,dots_lifetime)==0;

                            dots_X(deadDots) = (rand(1,sum(deadDots))-
.5)*(xRight-xLeft)+xLeft+Aperture_r;
                            dots_Y(deadDots) = (rand(1,sum(deadDots))-
.5)*(yBottom-yTop)+yTop+Aperture_r;


                        end
                    end
```

```
                end
                %%
                %%%for keyboard responses:
                Screen('DrawLines', MainWin, Fix_XY, 4, [0 255 0],[xCenter,
yCenter],2);
                Screen('Flip', MainWin);

                keyIsDown = 0;
                StartTime = GetSecs;
                correct=0;
                RT=0;

                while 1
                    [keyIsDown, timeSecs, keyCode] = KbCheck;
                    FlushEvents('keyDown');
                    if keyIsDown
                        nKeys = sum(keyCode);
                        if nKeys==1
                            if keyCode(First)||keyCode(Second)
                                RT = (timeSecs-StartTime);
                                keypressed=find(keyCode);
                                break;
                            elseif keyCode(EscapeKey)
                                ShowCursor; Screen('CloseAll'); return
                            end
                            keyIsDown=0; keyCode=0;
                        end
                    end
                end
                % ListenChar(0);


                if ((keypressed==CorrKeys(1) &&
StdDotSpeed(StdSpeedi)>TestDotSpeed(TestSpeedi))|| (keypressed==CorrKeys(2)
&& TestDotSpeed(TestSpeedi)>StdDotSpeed(StdSpeedi)))
correct = 1; % correct response of std>test
                elseif ((keypressed==CorrKeys(1) &&
StdDotSpeed(StdSpeedi)<TestDotSpeed(TestSpeedi))|| (keypressed==CorrKeys(2)
&& TestDotSpeed(TestSpeedi)<StdDotSpeed(StdSpeedi)))
                    correct = 0; %  correct response of std<test
                else
                    correct=2; %means either 1 or 2 was pressed when std and
test were equal
                end

                StdDotSpeedNow=StdDotSpeed(StdSpeedi);
                TestDotSpeedNow=TestDotSpeed(TestSpeedi);
                keypress=str2double(KbName(keypressed));
                if keypress==1
                    Faster="First";
                elseif keypress==2
                    Faster="Second";
                    %
                end
```

```
                if str2double(ConditionNow)==11
                    StdStim='Phi';TestStim='Phi';
                elseif str2double(ConditionNow)==12
                    StdStim='Phi';TestStim='RP';
                elseif str2double(ConditionNow)==22
                    StdStim='RP';TestStim='RP';
                elseif str2double(ConditionNow)==21
                    StdStim='RP';TestStim='Phi';
                end

                %%
                % write the data
                results=[ConstStimN Ntrials DotDirectionI1 DotDirectionI2
StdDotSpeedNow TestDotSpeedNow StdStim TestStim Faster correct StartTime
timeSecs RT];
                resultsAll=[resultsAll;results];


                WaitSecs(0.5);

            end
        end
    end
end
resultsHead = {'ConstStimN' 'Ntrials' 'DotDirectionI1' 'DotDirectionI2'
'StdDotSpeedNow' 'TestDotSpeedNow' 'StdStim' 'TestStim' 'Faster' 'correct'
'StartTime' 'timeSecs' 'RT'};
xlswrite(outputname,resultsHead,1,'A1');
xlswrite(outputname,resultsAll,1,'A2');

Screen('CloseAll');
```