

A Relation between Motion Opponency and Dichoptic Depth Cues

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The study of human perception is premised on the notion that our understanding of the external world is largely a mental construct. Even though it may provide useful information for navigating through and interacting with our environment, our perception is hardly a reflection of reality. Under certain circumstances, our perceptual systems may produce a faulty interpretation of the external world; in other situations, we may lose sensitivity to information which is normally salient. Motion opponency is one example from visual perception of the latter case. A number of studies have described the psychophysical and physiological traits of motion opponency and the visual stimuli which produce it (Heeger, D. J., Boynton, G. M., Demb, J. B., Seidemann, E., & Newsome, W. T., 1999; Levinson, E. & Sekuler, R., 1975; Lu, H., Qian, N., & Liu, Z., 2004; Qian, N., Andersen, R. A., & Adelson, E. H., 1994; Thompson, B. & Liu, Z., 2006). Together, these studies have found that motion opponency is characterized by a reduced sensitivity to motion direction when opposite motions are presented in a local area of the visual space, resulting in the percept of flicker or oscillation rather than transparent motion. This reduction in sensitivity is linked to strong suppression in visual area MT, which is considered to be largely responsible for motion analysis in the visual system.

Levinson and Sekuler (1975) were two of the earliest researchers to identify the effect of motion opponency experimentally. In their first experiment, participants observed sinusoidal luminance gratings which drifted either leftward or rightward. Participants could modulate the contrast of these test gratings. Each test grating was superimposed upon a background grating, which was either static or moving counterphase (in the opposite direction as the test grating). Participants were asked to lower the contrast of the test grating until the percept of the superimposed gratings was indistinguishable from that of a static grating raster. Levinson and

Sekuler found that the level of contrast chosen by participants in the static background case was lower than the level of contrast chosen in the counterphase background case. Presuming that a lower contrast threshold equates to greater sensitivity to the test grating, the researchers concluded that participants were better able to discriminate motion in the static background condition than in the counterphase background condition. The intention of their study was to substantiate an additive multi-channel theory of motion discrimination; however, this initial finding had an alternative explanation than Levinson and Sekuler's proposed theory. Although the effect of the counterphase superposition at threshold contrast could be understood as the result of two equally stimulated and oppositely tuned motion direction channels producing a zero sum, this superposition stimulus is, in reality, a flickering motionless image. Thus, it is also plausible that the visual system was not interpreting any motion information at all. To invalidate this alternative, the researchers generated a psychometric function using a two-alternative forced choice (2AFC) motion direction discrimination task, varying the difference in contrast between superimposed gratings. The result of this experiment was consistent with the multi-channel theory: participants were more sensitive to the motion direction of the higher contrast grating, with increasing sensitivity as the difference in contrast widened.

The work of Qian, Andersen, and Adelson (1994) expands upon the findings of Levinson and Sekuler by examining a particular aspect of motion perception that the multi-channel theory of motion discrimination cannot adequately explain: motion transparency. In many contexts, the visual system actually has no problem perceiving distinct and simultaneous motions occurring in the same area of the field of vision. Indeed, it is far more peculiar that a bidirectional motion display should not be perceived as transparent. Qian et al. investigated what properties of counterphase motion displays account for this inhibition of transparent motion perception by

searching for other nontransparent motion displays. By manipulating the sinusoidal grating display in clever ways, the researchers found that neither the spatiotemporal frequency nor the dimensionality of the elements in the display were determining factors in motion transparency; instead, their study implicated the local pairing of counterphase motions in nontransparent displays. To study this relationship experimentally, Qian et al. generated bidirectional dot motion displays in which varying percentages of the dots were paired with dots moving in counterphase. Participants were asked to observe these displays and rate them as either more or less transparent than a baseline animation in a 2AFC task. The data collected produced a very robust psychometric function indicating that displays with low percentages of counterphase pairing were perceived to be more transparent than displays with high percentages of counterphase pairing. The results of this experiment suggest that transparent motion perception is constructed from the synchrony of multiple motion-receptive areas; the inhibition of transparent motion perception may be the result of local opponent motion directions mutually suppressing one another within a single motion receptive area, preventing the transmission of useful information for constructing a global motion percept. In Qian and Andersen's study of the physiology underlying transparent motion perception, they found that the suppression of motion transparency was largely linked to the strong suppression of visual area MT, suggesting it does not encode motion information when observing the counterphase dot patterns.

The research of Lu, Qian, and Liu (2004) challenged this explanation by providing evidence that motion direction can still inform perceptual learning under nontransparent motion conditions, when area MT should be eliminated. After practicing a 2AFC motion axis rotation discrimination task within a small range of angles from vertical, the researchers were able to determine a baseline for participant performance on an unfamiliar task. Participants were then

trained on the same task in a different range of angles from vertical, with the variation that the stimuli were opponent and consistent with the effects observed in the work of Qian et al. After this training, participants were tested on the original task in the new angle range, and some of these participants demonstrated better than novice performance, suggesting that motion information was successfully utilized in perceptual learning under conditions in which area MT was presumably deactivated. One interpretation of this result is that, MT must still encode and make use of directional information under counterphase conditions, because perceptual learning would not be possible otherwise. Of course, learning is a very complex process, and it might be presumptuous to localize it to MT even if this visual area is highly correlated with motion perception tasks. Further work by Thompson and Liu (2006) demonstrated that motion direction discrimination was more difficult to learn in counterphase motion conditions than in unsuppressed inphase motion conditions. Given this result, and the fact that this kind of learning was not observed in all participants in the work of Lu et al., a better founded conclusion is that MT may directly contribute to motion discrimination learning but is not entirely necessary. Further research involving fMRI and MVPA may be able to better parse how perceptual learning happens and where this change in sensitivity manifests. Nonetheless, these results demonstrate the very specific and nuanced nature of motion opponency and the complexity of area MT.

Although many studies have investigated the finer characteristics which define motion opponency and its effect on the visual system, there is no consensus on whether this phenomenon has a functional purpose or is a side effect of other functions in the visual system. Our present study aims to further these questions by asking what relationship exists between motion opponency and binocular fusion, if any.

There is little research precedent regarding this specific question, but other studies not directly linked to motion opponency may be able to inform our hypotheses. A substantial breadth of literature examines the role of MT in extracting depth information. DeAngelis, Cumming, and Newsome (1998) investigated the role of visual area MT in stereopsis; in particular, they sought to answer the question of whether the presence of disparity-selective neurons in visual area MT actually contributes to stereoscopic depth perception. Using electrical microstimulation in monkeys, the researchers were able to reliably bias perception of depth and referred to their own 1997 study (text unavailable) which demonstrated the role of MT in the perception of depth from motion cues. In a similar study, Orban, Sunaert, Todd, Van Hecke, and Marchal (1999) employed fMRI to investigate brain regions involved in extracting three-dimensional structure from motion. They found that MT was more active when participants were observing three-dimensional displays, regardless of their rigidity; however, they found that MT was associated with activation of a right-hemisphere-dominant network and lateral occipital region which strongly correlated with perceived three-dimensional structure as it may be extracted from motion, rather than rigid two-dimensional cues for depth. This suggests that MT plays some important, but not necessarily central, role in depth perception through motion.

These insights do not disagree with the physiological measurements of Qian, Andersen, and Adelson (1994) and the psychophysical measurements of Lu, Qian, and Liu (2004): together these studies suggest a nuanced relationship between MT and motion in depth; however, the work of Maunsell and Van Essen (1983) indicate that this relationship may be far less explicit than we may intuit. Using single unit measurements on anesthetized monkeys, they found that no units whatsoever in visual area MT were selective for motion in depth. Any relationship between MT activity and motion in depth was indirect: for example, the result of sensitivity for

horizontal disparities. Incorporating the results from Orban, Sunaert, Todd, Van Hecke, and Marchal (1999), we may posit that visual area MT is, instead, preliminary to the perception of motion in depth, rather than immediately involved in it. What motivation then exists for the claim that suppression observed in MT under motion opponency is some compensation for motion in depth? We conjecture that MT is inherently insensitive to specific motions in depth, as suggested by the above literature. Furthermore, the information available to MT from earlier in the visual pathway does not allow it to distinguish between dichoptic cues for motion in depth and opponent stimuli. Thus, MT's insensitivity toward motion in depth generalizes to an insensitivity toward opponent stimuli, leading to suppression under opponent conditions.

More specifically, we hypothesize that opponent effects are the result of some perceptual aliasing that is introduced by the fusion of retinotopic images into a cyclopean representation. Barendregt, Harvey, Rokers, and Dumoulin (2015) demonstrated that, while V1 is best understood abstractly as encoding a binocular retinal representation of incoming visual information, the extrastriate cortex is better understood as encoding a cyclopean representation. While their study did not look at MT explicitly, this abstract understanding of information encoding may be critical to knowing exactly what visual information is available for MT to process. It may be that the V1 retinal representation includes data which does not translate to the cyclopean representation properly. Such a translation error may contribute to the peculiar nature of dichoptic stimulation.

Furthermore, Matthews, Geesaman, and Qian (2000) investigated the interaction between motion perception and binocular rivalry. They found that distant dichoptic motions which disagree in direction produced strong experiences of binocular rivalry, with the percept alternating between the two motion directions; however, when these disagreeing dichoptic

motions were presented to a more localized area of the visual space, this motion repulsion was replaced by the absence of motion perception altogether. This result suggests some aspect of binocular fusion which produces an effect not unlike motion opponency as described by Qian and Andersen: equally salient and disagreeing motions presented locally interfere with the comprehension of motion direction altogether.

Informed by these studies, our current research puts forth the following hypothesis: motion opponency will have a much more pronounced effect when counterphase motions are presented dichoptically rather than monocularly. If this is the case, it would suggest that motion opponency is the result of compensations made by the visual system to process stereoscopic cues for motion in depth, suppressing directional activation in MT to avoid misinterpreting motion toward the viewer as lateral motion. As demonstrated by Qian and Andersen, motion opponency depends on locality just as much as it depends on counterphase motion. Abstractly, we can intuit that certain egocentric motions in depth produce such local opposite motion directions in each eye. Matthews et al. demonstrated that localized dichoptic motion disagreements are resolved by the absence of lateral motion perception, aligning with the premise of our hypothesis. Given the translation between representations implicated by Barendregt et al., it may be that the opponent motions which are best understood retinotopically are being misinterpreted as dissonant motions related to a single object in space, as the cyclopean representation by definition tries to reconcile these disparities. Motion opponency would thus be more pronounced under dichoptic conditions, because the visual information provided in this case would better align with what the cyclopean image expects to see. This hypothesis does not disagree with the findings of Lu et al. and Thompson and Liu because it suggests that motion directionality is suppressed in MT while a different functionality of this visual area continues to work as expected, based upon aliased

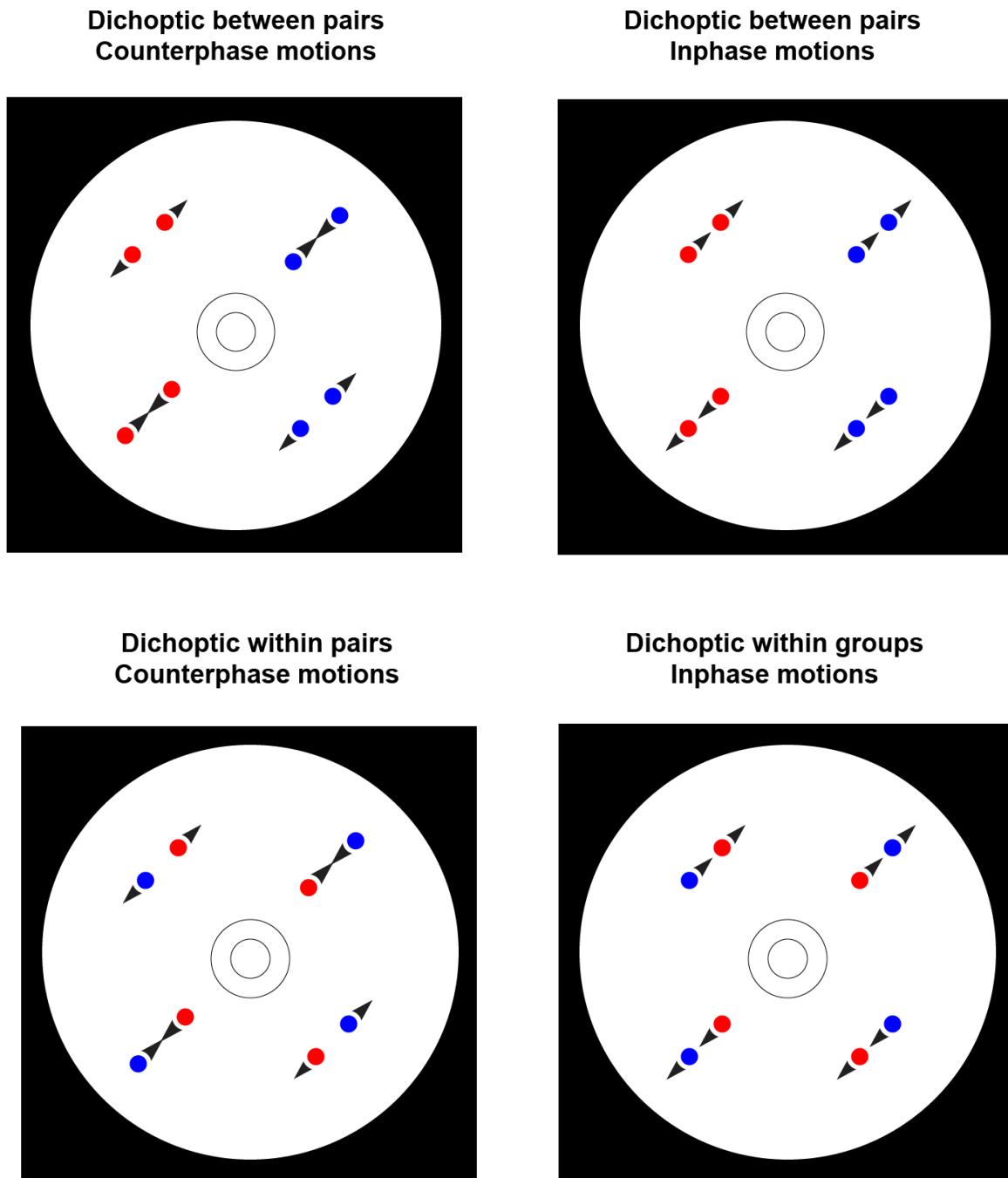


information. This research is very important, as it may reveal some useful disposition in our visual system, or an inherent vulnerability; understanding these peculiarities may inform how we design tools with which we interact and may reveal a bias in our understanding of the external world.

## **Method**

### **Participants**

Thirty-four undergraduate students participated in this experiment for research credit in one of their psychology courses at the University of California, Los Angeles. Each student received full participation credit for completing the experiment, regardless of their performance. All participants had normal or corrected-to-normal vision and were fluent in English.



*Figure 1.* Diagram of dot pair motion and coloration across all four experimental conditions. Dots of a particular color are visible to one eye and one eye only. In every condition, the dot field a single eye is presented contains bidirectional motion. The concentric fixation circles are visible during stimulus presentation. In all four images, the dot pair motion is clockwise from neutral.

## Design

The present study was conducted using a 2 x 2 x 5 within-subjects factorial design in which each participant provided a response to a 2AFC task regarding the preceding trial presentation. Each trial presentation belonged to one of four primary conditions, tested at one of five angles: 3°, 6°, 9°, 12°, or 15°. These values indicate the angle made by the intersection of the vertical axis and the axis of dot motion. Every dot in a single trial presentation moved parallel to this axis of motion, with half of all dots moving toward one pole and half moving toward the opposite pole. The rotational direction of the axis of motion's angle of offset from vertical was randomly assigned to be either clockwise or counterclockwise, with half of all conditions being offset clockwise and half being offset counterclockwise.

The four primary conditions tested at each of these angles and offsets are illustrated by Figure 1. The first primary independent variable was the stereoscopic separation of dots. This varied between two levels: dichoptic-within-pairs and dichoptic-between-pairs, implemented within the stimulus by variation of dot color. These colors corresponded to a pair of anaglyph glasses worn by participants. In the dichoptic-between-pairs condition, the dots in each pair were either both red or both blue; in the dichoptic-within-pairs condition, one dot in each pair was red and the other dot blue. In both conditions, an equal number of dots of each color were presented. The second primary independent variable was the phase of motion of dot pairs. Phase varied between two levels: counterphase and inphase. In the counterphase condition, dots within pairs moved either inward or outward with respect to the pair's centroid, with an equal number of pairs moving inward as outward. In the inphase condition, dots within pairs moved in unison toward one of the two poles of the axis of motion, with an equal number of pairs moving toward one pole as the other. In both conditions, half of all red dots moved toward one pole and half

toward the other; similarly, in both conditions half of all blue dots moved toward one pole and half toward the other.

The dependent variable of the experiment was the accuracy of a participant's responses to the 2AFC task. This task required participants to indicate whether the axis of dot motion was offset clockwise or counterclockwise from vertical. Accuracy was determined by the percentage of trials of a particular condition for which the participant correctly identified the direction of offset. Participants responded by button press, and were only able to respond with "clockwise" or "counterclockwise," and were required to provide one of these two responses to every trial presented to them.

### **Materials and Apparatus**

The experiment was conducted as a computer script, developed on Matlab R2014a, implementing the Psychophysics Toolbox Version 3 function library (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007). The experiment was run on a standard desktop PC running Windows XP and equipped with an ATi Radeon X300/X550/X1050 Series GPU. Task directions and experimental stimuli were presented on a ViewSonic Graphics Series G75f monitor using the built-in maximum contrast and minimum brightness settings. The refresh rate of the display was set at 100 Hz. A chin rest was provided to ensure that the participant's viewing position was consistent for the duration of the experiment. The viewing distance from the chin rest to the monitor screen was 57 cm. During the entirety of the experiment, participants wore red-blue anaglyph glasses.

The stimulus presentation for each trial lasted 200 ms and consisted of 100 dot pairs presented to each eye (400 dots total) within a circular aperture of  $8^\circ$  in visual angle. Each dot was  $0.06^\circ$  in diameter and moved at a velocity of  $4^\circ/s$ . These dots were presented against a

textureless white background. Screen area beyond the edges of the aperture was set to black and contained no visual information. Every pair of dots was related to another pair of dots, implementing the “twin pairs” design developed by Lu et al. (2004) to destroy evidence of a Glass pattern. Any single set of twin pairs remained on screen for a maximum of 200 ms. The initial distance between within-pair dots was randomized such that a random number of pairs would expire before the end of the 200 ms and presentation time. If a set of twin pairs expired within the time of a single stimulus presentation, a new set of twin pairs would be generated at a random location elsewhere within the aperture. Two black concentric circles were presented at the center of this aperture to provide a fixation point. After 200 ms, all of the dots were removed from the screen, leaving only the concentric fixation circles.

Participants provided responses using keystrokes. The ‘/’ character key mapped to the response “clockwise” and the ‘z’ character key mapped to the response “counterclockwise.” Participants were provided immediate feedback during the testing phase of the experiment: a short beep would sound whenever a participant responded to a trial incorrectly.

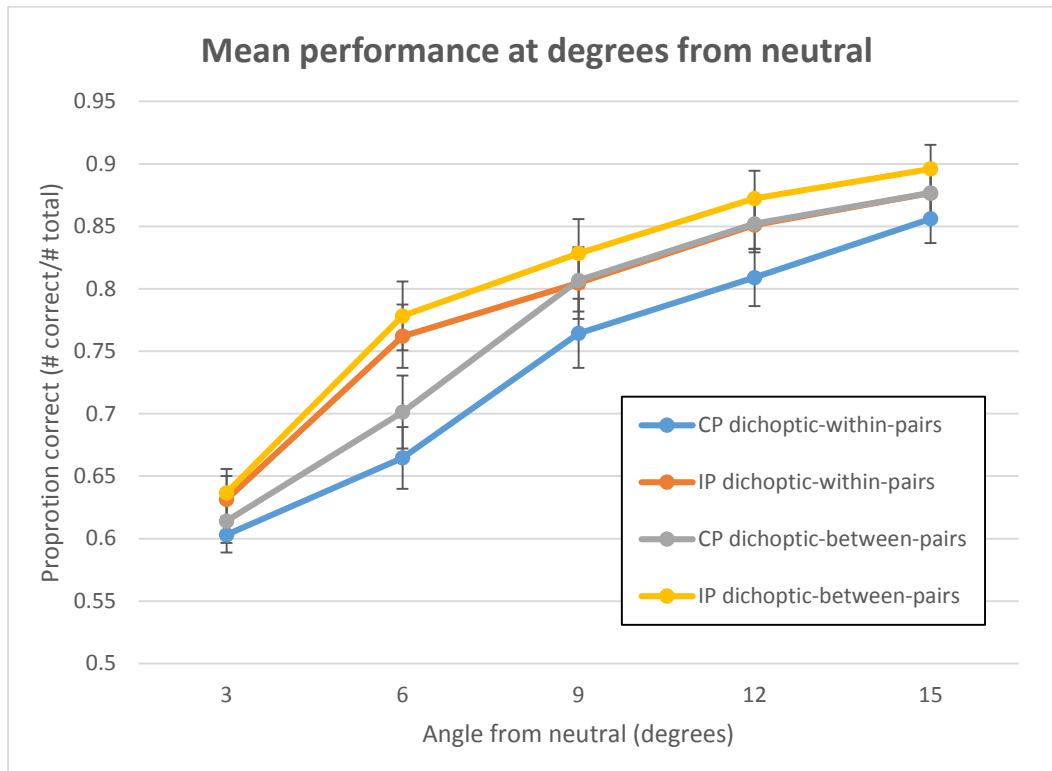
### **Procedure**

The experiment was composed of two phases: training and testing. During the training phase of the experiment, participants were exposed to 80 practice trials. The angle size of each trial became incrementally more difficult over the course of the training phase: the first trial used an angle size of  $45^\circ$  and the last trial used an angle size of  $5^\circ$ , with each subsequent trial using an angle size  $0.5^\circ$  smaller than the previous trial. Participants were free to respond at their own pace. A 500 ms delay was observed after each response before presenting a new trial. All four primary conditions were interleaved within the training block, and the direction of offset was randomly assigned and counterbalanced. Participants were provided immediate feedback during

the training phase. If participants performed below 60% during the training phase, they would be instructed to repeat the training phase until they had performed above this threshold.

During the testing phase of the experiment, participants were exposed 1600 trials, divided into ten blocks. Angle size was varied between blocks: the first five blocks tested each of the five angles in a random order, with the last five blocks following the reverse order of the first five blocks. Each block consisted of 160 trials. Forty of these trials were dedicated to each of the four primary conditions, interleaved in random order. The direction of offset of the axis of motion was randomly determined and counterbalanced within conditions within blocks. After every other block, a break would be provided following the performance summary. This break period was restricted to 30 seconds. Participants were informed when the experiment was about to resume by a five-second countdown with accompanying beeps. No break was provided after the final block. Once all the blocks had been completed, the script informed the participant that the experiment was over and automatically closed the task window.

## Results



*Figure 2.* Mean performance across all four experimental conditions for each of the five angles tested. Error bars indicate standard error for each condition for each angle. Range of the y-axis is from 0.5 to 1; performance of 0.5 is chance performance, corresponding to the least sensitivity for the task.



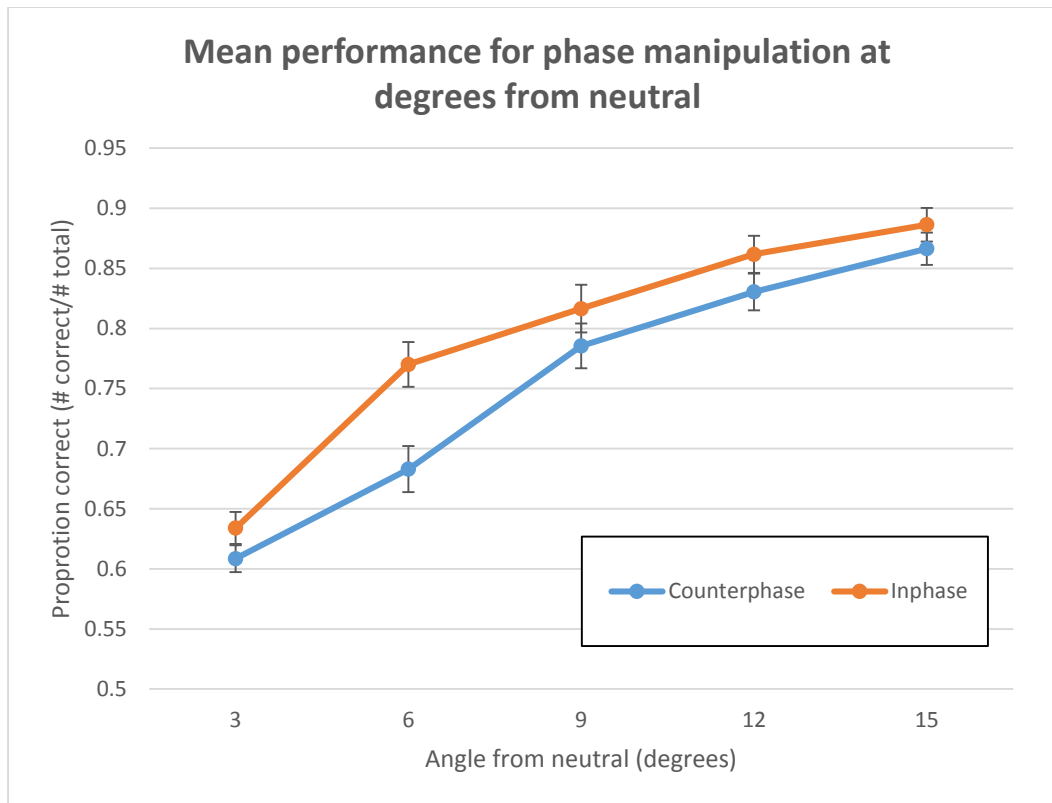


Figure 3. Mean performance across both counterphase conditions versus mean performance across both inphase conditions for each of the five angles tested. Error bars indicate standard error for each condition for each angle. Range of the y-axis is from 0.5 to 1; performance of 0.5 is chance performance, corresponding to the least sensitivity for the task.

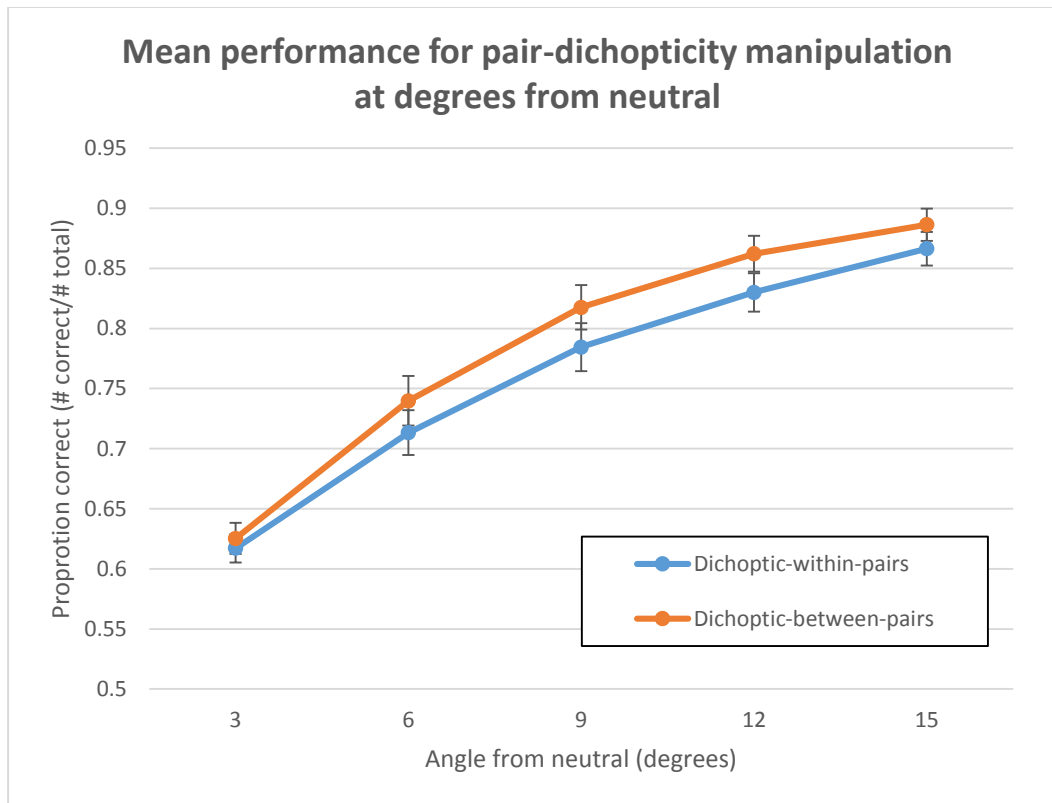


Figure 4. Mean performance across both dichoptic-within-pairs conditions versus mean performance across both dichoptic-between-pairs conditions for each of the five angles tested. Error bars indicate standard error for each condition for each angle. Range of the y-axis is from 0.5 to 1; performance of 0.5 is chance performance, corresponding to the least sensitivity for the task.

Of our 34 participants, four exhibited chance performance and were thus not included in our data analysis ( $N = 30$ ). Figure 2 illustrates the mean performance for each condition for each angle. A 2 x 2 within-subjects ANOVA was used to investigate the significance of any effects between phase and pair-dichopticity. This analysis revealed a main effect of phase across all five angles: as seen in Figure 3, performance on inphase trials was consistently and significantly higher than performance on counterphase trials at 3° from neutral,  $F(1, 29) = 4.212$ ,  $MSE = 0.019$ ,  $p < 0.05$ , at 6° from neutral,  $F(1, 29) = 78.79$ ,  $MSE = 0.228$ ,  $p < 0.001$ , at 9° from neutral,  $F(1, 29) = 9.696$ ,  $MSE = 0.029$ ,  $p < 0.005$ , at 12° from neutral,  $F(1, 29) = 19.32$ ,  $MSE = 0.030$ ,  $p < 0.001$ , and at 15° from neutral,  $F(1, 29) = 10.50$ ,  $MSE = 0.012$ ,  $p < 0.005$ .

We also found evidence for a main effect of pair-dichopticity across four of the five angles: as seen in Figure 4, even though performance on dichoptic-within-pairs trials was not significantly different than performance on dichoptic-between-pairs trials at 3° from neutral,  $F(1, 29) = 0.421$ ,  $MSE = 0.002$ ,  $p > 0.05$ , performance on dichoptic-within-pairs trials was consistently and significantly worse than performance on dichoptic-between-pairs trials at 6° from neutral,  $F(1, 29) = 4.577$ ,  $MSE = 0.020$ ,  $p < 0.05$ , at 9° from neutral,  $F(1, 29) = 11.30$ ,  $MSE = 0.032$ ,  $p < 0.005$ , at 12° from neutral,  $F(1, 29) = 15.38$ ,  $MSE = 0.030$ ,  $p < 0.001$ , and at 15° from neutral,  $F(1, 29) = 10.75$ ,  $MSE = 0.012$ ,  $p < 0.005$ .

There was no evidence for an interaction between these variables at 3° from neutral,  $F(1, 29) = 0.097$ ,  $MSE < 0.001$ ,  $p > 0.05$ , at 6° from neutral,  $F(1, 29) = 1.902$ ,  $MSE = 0.003$ ,  $p > 0.05$ , at 9° from neutral,  $F(1, 29) = 1.712$ ,  $MSE = 0.003$ ,  $p > 0.05$ , at 12° from neutral,  $F(1, 29) = 2.440$ ,  $MSE = 0.003$ ,  $p > 0.05$ , or at 15° from neutral,  $F(1, 29) = 0.003$ ,  $MSE < 0.001$ ,  $p > 0.05$ .

Given that the effect of pair-dichopticity was nuanced across angles, ten paired samples *t*-tests were conducted to better understand the simple effects between conditions. When dot pair motions were counterphase, we found that performance for dichoptic-within-pairs trials at 3° from neutral ( $M = 0.60$ ,  $SD = 0.08$ ) was not significantly different than performance for dichoptic-between-pairs trials ( $M = 0.61$ ,  $SD = 0.1$ ),  $t(29) = -0.69$ ,  $p > 0.05$ ; however, at 6° from neutral, performance for dichoptic-within-pairs trials ( $M = 0.66$ ,  $SD = 0.13$ ) was significantly worse than performance for dichoptic-between-pairs trials ( $M = 0.7$ ,  $SD = 0.16$ ),  $t(29) = -2.285$ ,  $p < 0.05$ . At 9° from neutral, performance for dichoptic-within-pairs trials ( $M = 0.76$ ,  $SD = 0.15$ ) was significantly worse than performance for dichoptic-between-pairs trials ( $M = 0.81$ ,  $SD = 0.14$ ),  $t(29) = -3.044$ ,  $p = 0.005$ . At 12° from neutral, performance for dichoptic-within-pairs trials ( $M = 0.81$ ,  $SD = 0.13$ ) was significantly worse than performance for dichoptic-between-

pairs trials ( $M = 0.85$ ,  $SD = 0.11$ ),  $t(29) = -3.851$ ,  $p = 0.001$ . At  $15^\circ$  from neutral, performance for dichoptic-within-pairs trials ( $M = 0.86$ ,  $SD = 0.11$ ) was, once again, not significantly different than performance for dichoptic-between-pairs trials ( $M = 0.88$ ,  $SD = 0.1$ ),  $t(29) = -1.66$ ,  $p > 0.05$ . In sum, for counterphase manipulations, performance for dichoptic-within-pairs trials was significantly worse than performance for dichoptic-between-pairs trials only at angles of  $6^\circ$ ,  $9^\circ$ , and  $12^\circ$ .

When dot pair motions were inphase, we found that performance for dichoptic-within-pairs trials at  $3^\circ$  from neutral ( $M = 0.63$ ,  $SD = 0.1$ ) was not significantly different than performance for dichoptic-between-pairs trials ( $M = 0.64$ ,  $SD = 0.1$ ),  $t(29) = -0.303$ ,  $p > 0.05$ . At  $6^\circ$  from neutral, performance for dichoptic-within-pairs trials ( $M = 0.76$ ,  $SD = 0.14$ ) was, once again, not significantly different than performance for dichoptic-between-pairs trials ( $M = 0.78$ ,  $SD = 0.15$ ),  $t(29) = -1.289$ ,  $p > 0.05$ ; however, at  $9^\circ$  from neutral, performance for dichoptic-within-pairs trials ( $M = 0.80$ ,  $SD = 0.16$ ) was significantly worse than performance for dichoptic-between-pairs trials ( $M = 0.83$ ,  $SD = 0.15$ ),  $t(29) = -2.155$ ,  $p < 0.05$ . At  $12^\circ$  from neutral, performance for dichoptic-within-pairs trials ( $M = 0.85$ ,  $SD = 0.12$ ) was significantly worse than performance for dichoptic-between-pairs trials ( $M = 0.87$ ,  $SD = 0.12$ ),  $t(29) = -2.065$ ,  $p < 0.05$ . At  $15^\circ$  from neutral, performance for dichoptic-within-pairs trials ( $M = 0.88$ ,  $SD = 0.11$ ) was significantly worse than performance for dichoptic-between-pairs trials ( $M = 0.9$ ,  $SD = 0.1$ ),  $t(29) = -2.759$ ,  $p = 0.01$ . In sum, for inphase manipulations, performance for dichoptic-within-pairs trials was significantly worse than performance for dichoptic-between-pairs trials only at angles of  $9^\circ$ ,  $12^\circ$ , and  $15^\circ$ .

### Discussion

The results of our study describe a significant effect of both phase and pair-dichopticity on motion axis sensitivity for a 2AFC motion axis rotation discrimination task, such that participants performed more poorly on counterphase conditions than inphase conditions across all angles tested, and more poorly on dichoptic-within-pairs conditions than in dichoptic-between-pairs conditions across four of the five angles tested. The difference in sensitivity observed between conditions of phase aligns with our predictions and the results of previous investigations of motion opponent phenomena (Levinson, E. & Sekuler, R., 1975; Lu, H., Qian, N., & Liu, Z., 2004; Qian, N., Andersen, R. A., & Adelson, E. H., 1994; Thompson, B. & Liu, Z., 2006): the reduction in sensitivity for transparent motion and motion direction are definitive characteristics of motion opponent phenomena. The observation of this effect in our study demonstrates consistency between our design and previous studies, and allows us to interpret our results with respect to variation in pair-dichopticity in comparison to past literature. Moreover, the psychometric function generated by performance across angles matches our expectations, with lowest performance at small angles and greatest performance at large angles.

Our experimental hypothesis was that, in the counterphase condition, we would observe a significant reduction in performance from the dichoptic-between-pairs condition to the dichoptic-within-pairs condition. Albeit inconclusive, our results tend to align with this hypothesis. For the middle three test angles, 6°, 9°, and 12°, we find that dichoptic-within-pairs separation leads to significantly poorer performance than the dichoptic-between-pairs condition. At 3° and 15° we observe a similar trend, albeit insignificant. We suppose that some weakness in this effect at the edge cases may be introduced by the inclusion of participants who demonstrated floor effects for the few hardest angles, and other participants who demonstrated ceiling effects for the few easiest angles. Although this may seem a promising result for our hypothesis, we are hesitant to

attribute it to some abstract motion and depth sensitivity heuristic like the one proposed earlier in this paper; this is because we observed no interaction between phase and pair-dichopticity as we had suggested.

Interestingly, we observe a similar but slightly less powerful effect within the inphase conditions: For the largest three test angles,  $9^\circ$ ,  $12^\circ$ , and  $15^\circ$ , we find that dichoptic-within-pairs separation leads to significantly poorer performance than the dichoptic-between-pairs condition. At  $3^\circ$  and  $6^\circ$  we observe a similar trend, albeit insignificant. This was not a result predicted by our hypothesis. In fact, it is possible that this result actually counter-indicates the explanation for motion opponency our research had initially intended to support: given that there is no interaction between phase and pair-dichopticity such that there is a significant effect of pair-dichopticity within counterphase conditions and no effect of pair-dichopticity within inphase conditions, it is plausible that the dichoptic separation of dots within pairs reduces sensitivity to motion direction in a way that is consistent and independent from the effects of motion opponency. This alternative appears to be better supported by our results than our initial hypothesis. Previous work (Blake et al., 1998) has demonstrated that, during binocular rivalry, one eye is suppressed while the other achieves visual dominance. Although dominance oscillates between eyes, the motion suppression felt by the inferior eye is nonselective, leading to reduced salience of all incoming information. It may thus be the case that within-pairs rivalry produces a stimulus that is simply less salient overall, compounding the effects of rivalry and motion opponency which manifests in significant effects between conditions of pair-dichopticity for both phases. It may be worthwhile for precluding our original hypothesis to verify such compounding of rivalry and opponent effects by comparing these performance measures with a

third condition of phase in which there is no rivalry whatsoever; rather a single eye observes what it would in a typical stimulus presentation, while the other eye observes nothing at all.

Moreover, the significant effects between pair-dichopticity conditions within the inphase condition at large angles discount the possibility that ceiling effects are responsible for the lack of a significant effect of pair-dichopticity at higher angles in the counterphase condition: since performance for inphase is consistently higher than performance for counterphase, any ceiling effect that would effect within-counterphase effects would affect within-inphase effects more so. Even, so, the results do not discount the possibility of floor effects weakening effect significance at smaller angles. However, given the reasoning above, we have very little evidence to suggest that there exists some interaction between dichoptic depth cues and motion opponency: pursuing significance at the edge cases does not seem liable to help confirm our experimental hypothesis.

Nonetheless, our results do arouse some interesting questions. For example, if the effect of binocular rivalry is to give one eye dominance and to unselectively suppress motion information in the opposite eye, why are the counterphase dichoptic-within-pairs and inphase dichoptic-within-pairs conditions not comparable? Why is it that binocular rivalry does not instead alleviate the effects of motion opponency? Moreover, is there some meaningful significance in the strong similarity between performance for the inphase dichoptic-within-pairs and the counterphase dichoptic-between-pairs conditions? Is it just coincidence that this pattern breaks at  $6^\circ$  from neutral? Although the inability to observe the expected interaction between phase and pair-dichopticity undermines our hypothesis that motion opponency is the result of some functional inhibition of lateral motion perception, the questions we pose above inspire us to continue to consider what relationships may exist between visual area MT's selectivity for planes of depth and the suppression which occurs in visual area MT under motion opponency. To

answer such questions would provide us a better understanding of motion perception and integration in the visual system.



### References

- Barendregt, M., Harvey, B. M., Rokers, B., & Dumoulin, S. O. (2015) Transformation from a Retinal to a Cyclopean Representation in Human Visual Cortex, *Current Biology*, 25, 1982 - 1987.
- Blake, R., Yu, K., Lokey, M., & Norman, H. (1998). Binocular rivalry and motion perception. *Journal of Cognitive Neuroscience*, 10(1), 46-60.
- Brainard, D. H. (1997) The Psychophysics Toolbox, *Spatial Vision*, 10, 433 - 436.
- DeAngelis, G. C., Cumming, B. G., & Newsome, W. T. (1998). Cortical area MT and the perception of stereoscopic depth. *Nature*, 394(6694), 677-680.
- Heeger, D. J., Boynton, G. M., Demb, J. B., Seidemann, E., & Newsome, W. T. (1999). Motion opponency in visual cortex. *The Journal of Neuroscience*, 19(16), 7162-7174.
- Kleiner, M., Brainard, D., & Pelli, D. (2007) "What's new in Psychtoolbox-3?" Perception 36 ECVF Abstract Supplement.
- Levinson, E. & Sekuler, R. (1975) The independence of channels in human vision selective for direction of movement. *The Journal of Physiology*, 250(2), 347 - 366.
- Lu, H., Qian, N., & Liu, Z. (2004) Learning motion discrimination with suppressed MT. *Vision Research*, 44, 1817 - 1825.
- Matthews, N., Geesaman, B. J., & Qian, N. (2000) The dependence of motion repulsion and rivalry on the distance between moving elements. *Vision Research*, 40, 2025 - 2036.
- Maunsell, J. H., & Van Essen, D. C. (1983). Functional properties of neurons in middle temporal visual area of the macaque monkey. I. Selectivity for stimulus direction, speed, and orientation. *Journal of neurophysiology*, 49(5), 1127-1147.

- Orban, G. A., Sunaert, S., Todd, J. T., Van Hecke, P., & Marchal, G. (1999). Human cortical regions involved in extracting depth from motion. *Neuron*, 24(4), 929-940.
- Pelli, D. G. (1997) The VideoToolbox software for visual psychophysics: Transforming numbers into movies, *Spatial Vision*, 10, 437 - 442.
- Qian, N., Andersen, R. A., & Adelson, E. H. (1994) Transparent Motion Perception as Detection of Unbalanced Motion Signals. I. Psychophysics, *The Journal of Neuroscience*, 14(12), 7357 - 7366.
- Qian, N. & Anderson, R. A. (1994) Transparent Motion Perception as Detection of Unbalanced Motion Signals. II. Physiology, *The Journal of Neuroscience*, 14(12), 7367 - 7380.
- Thompson, B. & Liu, Z. (2006) Learning motion discrimination with suppressed and un-suppressed MT, *Vision Research*, 46, 2110 - 2121.