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ADULT OBSERVERS' SENSITIVITY TO OPTIC FLOW VARIES
BY PATTERN AND SPEED

WILLIAM ADAMIAK
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Reviewed and approved* by the following:

Rick Owen Gilmore
Associate Professor of Psychology
Thesis Supervisor

Gong Chen
Professor of Biology
Honors Adviser

Richard Alan Carlson
Professor of Psychology
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

ABSTRACT

In adults, radial optic flow evokes stronger brain activity than linear or rotational flow. Optic flow also evokes different activation patterns depending on motion speed (Fesi et al., 2014). This study examined whether the detection of optic flow in adult observers varies by pattern and speed in ways consistent with prior physiological evidence. Adult observers viewed two side-by-side, time varying optic flow displays that varied in pattern type and speed while judging which side contained coherent motion. As predicted, proportion correct judgments increased with motion coherence, and the response time of correct judgments declined. Observers more rapidly and accurately detected radial flow patterns, but there were no main effects of speed. Taken together the results suggest that behavioral sensitivity to detect optic flow in noise varies by pattern type and speed, in ways partially consistent with prior physiological results. This research is important as it provides baseline data for further experimentation with optic flow displays, which could be developed into novel screenings for perceptual abilities.

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Chapter 1

Background

Mobile organisms must accurately determine their direction of self-motion, or ego-motion, as they move through an environment. In activities like driving, sports, or everyday ambulation, motion perception is vital. The visual system is constantly responsible for picking up details about objects in densely populated environment, like edges, contours, colors, and shades. The brain compiles these visual stimuli to supply an organism with its percept of an environment. These details alone are not sufficient for the brain to comprehend every feature of an environment. For full mapping of the 3D layout of a setting, more information must be gathered about depth. The addition of motion in an environment and the resulting perceived motion perception is what provides the necessary details about depth in a 3D environment.

A moving observer or object generates what is known as optic flow. Optic flow provides a depth map of 3D layout and allows perceivers to steer in complex environments and perceive events (Pan & Bingham, 2013). In a stationary visual environment, the only available perceptual input is image structure. Adding events, or motion, allows for the perception of change in an environment. The brain is able to extract spatial information from motion by comparing the differences between the distinct still frames that exist within events. From motion perception, organisms are able to perceive their direction of heading as they move through an environment. Perceived heading enables organisms to control body posture, avoid collisions, and quickly and efficiently move through their environments (e.g., Gilmore, Baker, & Grobman, 2004).

The concept of optic flow was originally intended to describe the pattern of motion that occurs on the retinae as an organism moves (Gibson, 1950). Optic flow consists of the various streams of motion that come from features of the surrounding environment during self-motion (Cutting et al., 1992). An organism's perception of optic flow provides information about the direction and speed of the observer and the layout of surfaces in the environment (Gibson, 1979). Regional differences in optic flow create what is referred to as motion contrast, which allows for visual segmentation between different objects in an environment. Essential to the concept of optic flow are the concepts of local motion and global motion.

Local motion processing refers to the brain's detection of direction and speed of motion at a particular point in space (Weinstein et al., 2012) and within a small region surrounding it. This can be understood by thinking about the motion of a single dot upon a screen. Perception of biological motion, which is the visual signal associated with a moving, animate object, requires the integration of local motion information over time and space (Freire et al., 2005). The integration of local motion signals gives rise to what is known as global motion. Global motion refers to the patterns generated by a group of points in space displaying coherent, synchronous motion. Computational analysis has been able to show that all optic flow patterns can be decomposed into a combination of basic vector fields of global motion (Koenderink, 1986). The basic patterns of optic flow that are generated by global motion detection include linear flow, radial flow, rotational flow, and shear flow or deformation (Figure 1). Radial flow is considered to be the dominant pattern of optic flow. Radial expansion would be associated with forward translation through depth (De Jong et al., 1994).

From a biological perspective, a goal is to map how the brain deciphers what the eyes take in. Visual inputs are processed differentially by specific brain areas. Numerous

physiological and behavioral studies have been dedicated to learning which brain areas are activated during the various aspects of motion processing. In primates, motion signals are captured by motion direction selective cells in the primary visual cortex, or V1 (Hubel & Wiesel, 1968). This part of the cerebral cortex is responsible for processing the simple visual information received from the eyes. Much is still unclear about the how the brain conducts higher order motion processing. Past neurophysiological studies conducted on both monkeys and humans have helped to establish the importance of the middle temporal (MT) area of the macaque and its homologous area in humans, V5 or hMT. This brain area has been shown to play a vital role in motion integration (Born & Bradley, 2005; Britten et al., 1992). Experimental lesions to this area in the macaque causes selective impairment to the organism's motion perception abilities (Newsome & Pare, 1988). A number of recent fMRI studies have implicated other brain regions in playing roles in motion perception. In response to viewing different types of global motion patterns, the areas V6 (Cardin & Smith, 2010; Cardin et al., 2012), human MST (Cardin et al., 2012), and the posterior cingulate (Fischer et al., 2012) have been shown to be differentially activated, depending on the stimulus type.

Another branch of research has focused on how these brain areas and their activation change over the course of human development. One method of doing this is comparing the steady-state visual evoked potential (SSVEPs) response profiles, which are measured using electroencephalography (EEG), of infants and adults. Current research suggests that there is a prolonged developmental period before the fully mature motion processing network is established. Adults and infants show similar SSVEP response profiles to local motion, but strongly differ in response to rotational optic flow patterns with temporally modulating motion coherence (Hou et al., 2009). Infants show the strongest brain responses to stimuli at large

displacements/fast speeds, while adults show strongest responses at small displacements/slow speeds, indicating a clear developmental change in the motion perception brain network.

Behavioral studies have been performed on both monkey (Kiorpes & Movshon, 2004) and human children (Hadad, Maurer, & Lewis, 2010) to support the physiological evidence of this sensitivity shift. For specific optic flow patterns, infants show the largest SSVEPs to direction-reversing linear flows and adults show the largest SSVEPs to radial flows (Gilmore et al., 2007). This finding verifies that the human visual system undergoes prolonged development in higher order motion processing.

To further understand motion processing within adults, Fesi et al., (2014) investigated the effects of pattern and speed of optic flow patterns on SSVEP response sensitivity. The results of the study indicated that the evoked cortical responses associated with the temporal modulation of coherent global motion do indeed differ across different patterns and speeds, although the effects of each vary by channel, or brain area. SSVEP responses in the medial and lateral channels were found to be stronger for radial optic flow patterns than for translation or rotation. The distribution of the brain responses to radial flow differed when speed was altered. At slow speeds, strong bilateral activation was seen, while more dorsomedial activation was seen at faster speeds. Similar shifts were seen in the other flow patterns as well but to a lesser degree. Across all three patterns, SSVEP amplitudes increased as speed increased. At faster speeds, responses to all patterns looked increasingly similar, indicating pattern general motion processing at high speeds. Taken together, these findings indicate differential recruitment of brain circuits sensitive to different speed and pattern combinations.

The lateral brain activation patterns seen in response to radial flow are likely associated with the activation of hMT or MST brain area. As previously stated, radial flow is the dominant pattern of optic flow and is representative of an observer experiencing forward translation through depth (De Jong et al., 1994). Many studies have already identified MST as being important in detecting the flow patterns associated with self-motion (Duffy & Wurtz, 1991, 1997; Huk, Dougherty, & Heeger, 2002; Komatsu & Wurtz, 1988).

The medial occipital cortex activation seen in response to slow rotation and translation likely represent less dominant optic flow components that are imposed by head and eye movements. The optic flow patterns associated with these movements are less likely to reflect the structure of the 3D environment in which the observer is immersed (Britten, 2008). The pattern ambiguous activation of the dorsomedial occipital brain regions likely reflects activity in area V3a. This area, and surrounding areas such as V7, regions of the intraparietal sulcus, V6, and the posterior cingulate, have been shown to be involved in various aspects of depth processing (Backus et al., 2012), spatial attention (Behrmann, Geng, & Shomstein, 2004), motor intentions (Andersen et al., 2012), and navigation (Bremmer, 2005). It is likely that these brain areas, being activated by slow rotation and translation, are sensitive to changes in depth structure of an environment, as opposed to forward translation through that environment.

Together, the results of Fesi et al. (2014) suggest that optic flow patterns engage a network of brain areas beyond lateral regions such as MT and MST, as had been assumed in prior studies (Hou et al., 2009; Wattam-Bell et al., 2010). This research is important as it contributes to the understanding of adult brain function and proper development of global motion sensitivity. Measuring SSVEP responses to optic flow stimuli has been used to evaluate perceptual deficits

in patients with cerebral visual impairment (CVI) such as amblyopia and strabismus (Weinstein et al. 2012). Continued research into optic flow and associated brain activity could potentially lead to development of perceptual tests to supplement standard visual examinations.

The purpose of the current study is to extend the findings of Fesi et al. (2014) by testing whether behavioral evidence supports the physiological brain activation patterns caused by optic flow. In other words, this study investigates whether heightened brain activity corresponds to a facilitated identification of optic flow patterns. The study examines the effects of coherence level, pattern, and speed on how successful participants are at discriminating between global motion and random noise. It is predicted that coherence level will have a strong effect on participants' success rates and also their response rates. Based on the findings that SSVEPs were stronger for radial than other flow patterns, and also at higher speeds, it is predicted that participants will have an easier time identifying radial flow at high speeds. An interaction effect between pattern and speed is also predicted due to the finding in Fesi (2014) that brain responses to all patterns became increasingly similar at high speeds.

Chapter 2

Methods

Participants

30 adults (14 male, 16 female; age range: 18.7-23.9; mean age: 20.8 years) were recruited from the Pennsylvania State University campus to participate in the study. Subjects were recruited from an undergraduate subject pool for credit or were given \$10 per hour for their participation. All participants had normal vision or wore glasses or contact lenses. One participant's data was removed from analysis for failure to follow task instructions.

Display

The stimulus was generated using the program MATLAB on an iMac desktop computer. The program produced a display that consisted of a fixation point in between two circular random dot kinematogram displays. Each trial, one of the dot displays exhibited a coherent global motion pattern while the other exhibited completely random (0% coherent) dot motion (Fig. 2). Two separate dot display programs were made. In one, the dots of the kinematogram display moved at 2 deg/s and in the other the dots moved at 8 deg/s. Each program consisted of 4 blocks of 16 trials each.

Procedure

After securing informed consent, participants were guided to a dimly lit room for testing. Participants were given a brief explanation of local motion, global motion, and optic flow and then situated at a distance of 60 cm directly in front of the testing monitor. Participants were instructed to fixate on the dot in the center of the display and to use their peripheral vision to discern which of the displays was exhibiting an optic flow pattern. They were informed about the 10 second response limit and that their response times were being recorded. Participants used a keyboard to make their decisions, pressing the “z” key to choose the left and the “/ or ?” key to choose the right. Each participant was asked to complete two runs of 2 deg/s patterns and two runs of 8 deg/s patterns in an order that varied for each participant. Each run consisted of five testing blocks. The two optic flow patterns used were radial and translational motion. The four coherence levels used were 5%, 10%, 15%, and 20%. Each of the 8 combinations of coherence types and coherence levels appeared once on the left display and once on the right display for a total of 16 conditions within a block. A method of constant stimuli was used, and condition order varied randomly within a block. Participants were given the option to take a break half way through the experiment.

Analysis

The MATLAB program delivered data outputs for each session that had both response times for each trial and percent chosen correctly. Custom R scripts merged and cleaned the files prior to analysis. RStudio was used for statistical analysis and generate summary plots. The effects of speed, pattern, and coherence were analyzed using repeated measures analysis of

variance (ANOVA). Prior to conducting statistical analyses, all data were plotted and evaluated visually. As a consequence, one participant's data (14) was eliminated from analysis for having chance or worse than chance performance even at the highest coherence levels.

Chapter 3

Results

In order to determine whether participants are faster to respond to one type of optic flow or another as predicted by prior EEG evidence, a mixed effects ANOVA with RT as the dependent variable and optic flow pattern (2 levels: radial, translational) was run. Since the study also varied coherence levels (4 levels: 5, 10, 15, and 20%) and speeds (2 levels: 2 deg/s, 8 deg/s) in a totally crossed design, these factors were included in the ANOVA as well. The effect of coherence was modeled as a single linear predictor equivalent to slope because prior literature and theory suggest that response functions are continuous. The ANOVA included a separate random effect for each participant to account for the fact that reaction times vary widely across participants.

The descriptive statistics, including means, standard errors of the means, and medians, for response time data across coherence, pattern, and speed are reported in Table 1. Response times decreased as coherence level increased from 0.05 ($M = 3.90s$) to 0.20 ($M = 2.16s$). There was also a greater mean response time to linear ($M = 3.09s$) than to radial flow ($M = 2.81s$). Response times were very similar for optic flow patterns delivered at 8 deg/s ($M = 2.97s$) and at 2 deg/s ($M = 2.93s$). The response time means are displayed in a boxplot in Figure 4. The trends that can be visualized in this graph are that mean response times were shorter at higher motion coherence levels and for radial optic flow patterns. No effect of speed can be identified. The ANOVAs run confirmed main effects of coherence, $F(1, 455) = 229.84, p < 2e-16$, and pattern, $F(1, 455) = 10.55, p = 1.25e-3$, and no main effect of speed, $F(1, 455) = 0.15, p = 0.70$. The ANOVA results

indicate that alterations of the dependent variables coherence and pattern type have a significant effect of the amount of time participants took to respond in the task. These main effects were predicted, but cannot be fully evaluated without looking at the interaction effects present.

A significant two-way interaction was found between pattern and coherence, $F(1, 455) = 39.27, p = 3.85e-10$. This interaction indicates an effect of pattern, within the effect of coherence. In this scenario, an increase in coherence causes a drop in response time for both radial and linear patterns, but the effect is more extreme and the time decrease is more substantial for radial. In Figure 4, this interaction can be explained visually as a steeper decrease in response time means across coherence levels for radial than for linear optic flow patterns. There were no interaction effects found between speed and coherence or pattern and speed for the response time. Full ANOVA results for response time are listed in Table 3.

The other experimental measure used to evaluate perceptual abilities in identifying optic flow patterns was percent correct. Just as spending less time in answering was an indication of how easy a certain pattern is to identify, so is percent correctly identified. To determine whether participants were more successful at identifying one type of another, with predictions again based on the same EEG evidence, a mixed effects ANOVA with percent correct as the dependent variable and pattern type, coherence level, and speed as the independent variables.

For the percent correct data, the means, standard errors of the means, and medians across all conditions are given in Table 2. Success rates improved as the coherence level increased from 0.05 ($M = 0.52$) to 0.20 ($M = 0.90$). Success rates were found to be better for radial ($M = 0.76$) than for linear flow patterns ($M = 0.72$). There was little difference in success rates to flow patterns at 8 deg/s ($M = 0.73$) and 2 deg/s ($M = 0.75$). The trends that emerged from looking at the means were confirmed by the ANOVA. Main effects were found of coherence, $F(1,471) =$

423.42, $p < 2e-16$, and of pattern, $F(1, 471) = 9.94$, $p = 1.72e-3$, but not of speed, $F(1, 471) = 3.26$, $p = 0.07$. The success rates of each participant to each experimental condition are shown in Figure 3. Although each participant's success rate is shown individually, the trends found in the data analysis are still evident. Success rates increase at higher coherence levels and success rates are on average higher to radial than linear optic flow. Again, these main effects cannot be sufficiently analyzed without exploring the interaction effects present.

A significant interaction was found between pattern and coherence on participant success rates, $F(1, 471) = 19.48$, $p = 1.26e-5$, meaning that there was an effect of pattern within the effect of coherence. Participants were more successful at identifying optic flow at higher coherence levels regardless of pattern, but the degrees to which success rates increased varied between radial and linear. At low coherence levels (0.05) participants were more successful at detecting linear flow ($M = 0.54$) than radial flow ($M=0.49$) patterns. As coherence levels increased, participants showed a steeper rate of improvement at identifying radial than linear flow. At high coherence levels (0.20), participants were more successful at identifying radial ($M=0.96$) than translational ($M=0.86$) patterns. This interaction effect can be summarized as an increased sensitivity to radial flow patterns compared to linear flow patterns, at high coherence levels. In Figure 3, it is evident that at low coherence levels, participants have similar widespread success rates for both radial and translational. At high coherence levels, a larger cluster of participants achieved perfect success rates (1.00) for radial than for translational, illustrating the interaction between coherence and pattern. Overall, the slopes of the percent correct lines are steeper for radial than for linear patterns. No other interactions were found to exist for percent correct results. Full ANOVA results for the effects of coherence, pattern, and speed on percent correct are listed in Table 4.

Chapter 4

Discussion

Optic flow patterns and speeds influenced adult observers' abilities to detect coherent motion relative to noise. Participants were faster to detect coherent radial flow. A shorter response time indicates an easier time discerning between coherent global motion and random dot motion. Percent correct data offered parallel support to the response time data. Percent correct data analysis showed similar effects of coherence level and pattern type. Participants were more accurate in their identifications of global motion patterns for radial than translational flow. No main effect of speed was seen in either response time or percent correct data. This result indicates that adults are just as adept at identifying optic flow patterns at low speeds, 2 deg/s, as they are at high speeds, 8 deg/s under these unspeeded testing conditions.

The strong main effect of coherence level on response time and percent correct confirms prior predictions. The coherence level variable represents the percentage of dots in the display that are moving coherently. At the .05 coherence level, 95% of the dots in the display are still exhibiting random motion. The experimental data supports the logical assumption that it would be easier to detect optic flow patterns when a higher percentage of the display is exhibiting the pattern. The main effects of pattern type supported findings from a prior EEG study (Fesi et al. 2014). Fesi and colleagues found that radial global motion elicited stronger SSVEPs than linear motion responses in adults. The results of the current study provide evidence that human

behavior in identifying different optic flow patterns varies in ways similar to brain responses. On the other hand, Fesi (2014) found an effect of speed, which was not seen in this experiment.

Interaction effects were found between pattern and coherence on both response time and percent correct data. Depending on pattern type, an enhancement of coherence level resulted in different rates of increase for success rate and decrease for response time. A faster increase was seen in success rate across coherence levels for radial than linear motion. Similarly, a faster decrease in response time was recorded across coherence levels for radial than linear motion. This interaction could possibly indicate that brain areas involved in radial motion perception, like hMT or MST, are more sensitive to increases in coherence level than are the brain areas involved in linear global motion perception, like V3a, V6, and V7. This is speculative since no predictions were made about this hypothesis because Fesi (2014) did not involve altering coherence.

Despite the prediction that speed would have an effect on response time and success rates, no main effects of speed were found. Fesi et al. (2014) found heightened dorsomedial channel activation to faster display speeds. According to the results of the current experiment, this heightened brain activity may not result in more accurate judgments or shorter response times to faster speeds. Fesi et al. (2014) also reported that at higher speeds, brain responses to different optic flow patterns became increasingly stereotyped. This finding would have been supported by an interaction effect between pattern and speed. At 8 deg/s, response times and percent correct would have become more similar than they were at 2 deg/s. This trend was not observed, however.

A possible reason for this disparity between the two studies on the effect of speed was the contrasting experimental conditions. The EEG study recorded the immediate brain responses that were evoked as a response to viewing optic flow. In the current study, each trial had a ten second

response limit. Fesi (2014) measured optic flow responses that occurred over much shorter time periods, on the order of .5-1.5 s. Although we assume that similar brain responses were triggered by the displays in the current experiment, we recorded participants' conscious, behavioral responses. It is possible that the conscious element involved in the task diminished the noticeable effects that speed has on global motion detection.

There are several other limitations to the experiment. While Fesi (2014) investigated the effects of three optic flow patterns (radial, linear, and rotational), the present study only tested radial and linear. Rotational flow, like linear flow, is highly associated with observer head and eye movements. The scope of the current study did not include rotational optic flow patterns, but the groundwork has been laid for future studies to include them. Other patterns, like shear, and other speeds could also be tested in a series of motion coherence studies, for which the baseline data now exists.

Another limitation to be considered is that the current study involved the use of a central fixation point and peripheral viewing of the stimuli, while Fesi (2014) utilized a central view and a single display. Optic flow perception may differ in the periphery of the eye from the center of the visual field. Participants were not monitored nor was an eye tracker used so there is no guarantee that focus was kept on the fixation point. The decision was made to use side by side displays to allow for direct comparison between the two displays. The experimental design will also allow for continued optic flow experimentation on infants and children to track the development of the brain areas involved in motion perception.

As with most tasks, there is a learning effect of performing it repeatedly. Since every participant completed four runs for the experiment, two at 2 deg/s and two at 8 deg/s, there was the risk that participants would be more adept at recognizing optic flow patterns in the later runs,

regardless of conditions. To control for this, the order in which runs were delivered was systematically randomized and recorded. The effect of run order could be analyzed in future studies and if effects are found significant, steps could be taken to avoid this habituation to the study, such as voiding the first and last runs. This could also help to decrease the potential for the effect of participant tiring. The displays used in this experiment are perceptually draining, which poses the risk of participants becoming tired or losing interest as the experiment goes on. The effects of block and run on response times were plotted and visually inspected but no obvious deviations from the overall trend of the data were noticed. These effects likely add minor imprecision to the statistical calculations made.

Within a run of a program, it was decided to use a method of constant stimuli rather than a staircase procedure. In psychophysics, the method of constant stimuli dictates that stimuli are chosen from a constant fixed set, but are delivered in a completely random order. A staircase procedure, on the other hand, would begin with a high intensity stimulus, which is easy to detect, and decrease in intensity until the participant is incorrect. The trend repeatedly reverses and the values at which the reversals occur are recorded and averaged to determine the detection thresholds. The method of constant stimuli was used to prevent participant habituation to the order of stimuli and to enable movies to be generated in advance.

Another limitation to the current study is that kinematograms, or dot displays, may not tap the same perceptual abilities as optic flow in the real world does. These dot displays are designed to simulate the optic flow patterns that exist in nature, but they could still be perceived very differently. Navigation through an environment requires instantaneous motion perception. Ten seconds of every day visual input consists of hundreds of different optic flow patterns. In this study, participants were shown the same optic flow pattern for a ten second period, which is

a period that rarely occurs in nature. Motion perception over a prolonged period such as that is very different from what the real world demands. As a consequence, this experiment is only assessing detection of the most rudimentary elements of optic flow.

Continuation of psychophysical experiments on motion coherence is an important endeavor. This experiment represents a major stepping-stone in the field as it is very easy to replicate and build upon. Future researchers can easily modify the existing MATLAB program to include additional optic flow patterns or other parameters. All data collected has been uploaded to Databrary.com to allow for open data sharing and enable the continuation of the research. Further investigations into optic flow could potentially revolutionize perceptual screenings in the world. Optic flow kinematogram based perceptual tests could be used to evaluate if a person is capable of safely operating a car or being a fighter pilot in the military. Much still needs to be learned before this can become a reality, but this study provides a framework for how this can be achieved.

Appendix A

List of Figures

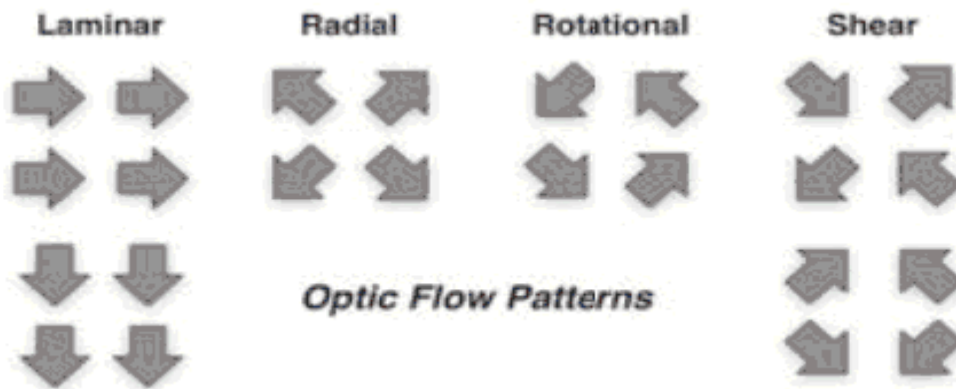


Figure 1: Types of Optic Flow Patterns. Laminar also known as translational/linear.

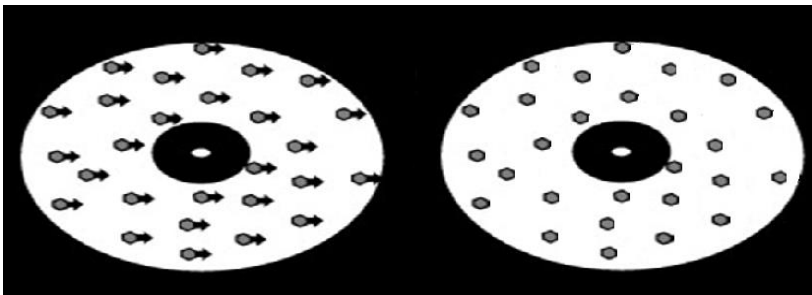


Figure 2: Experimental Set Up. Linear Coherent Motion in Left Display

Table 1: Descriptive Statistics of Response Time by Pattern, Coherence and Speed

	Linear			Radial		
	Coh	Mean RT (SEM)	Median RT	Coh	Mean RT (SEM)	Median RT
2 deg/sec	0.05	3.9594 (0.0913)	3.6198	0.05	4.0218 (0.0917)	3.6451
	0.10	3.3587 (0.0829)	2.8690	0.10	3.2069 (0.0751)	2.7704
	0.15	2.5241 (0.0604)	2.3109	0.15	2.0805 (0.0540)	1.7182
	0.20	2.4627 (0.0674)	2.2019	0.20	1.8893 (0.0543)	1.3847
8 deg/sec	0.05	3.8079 (0.0930)	3.3364	0.05	3.8049 (0.0931)	3.2360
	0.10	3.3632 (0.0852)	2.7987	0.10	3.2144 (0.0812)	2.6695
	0.15	2.8362 (0.0769)	2.4855	0.15	2.4746 (0.0691)	2.0850
	0.20	2.4655 (0.0715)	2.0435	0.20	1.8115 (0.0503)	1.3125

Table 2: Descriptive Statistics of Percent Correct by Pattern, Coherence, and Speed

	Linear			Radial		
	Coh	Mean P. Corr (SEM)	Median P.Corr	Coh	Mean P.Corr (SEM)	Median P.Corr
2 deg/sec	0.05	0.5569 (0.0266)	0.55	0.05	0.4759 (0.0227)	0.45
	0.10	0.7580 (0.0233)	0.80	0.10	0.7132 (0.0359)	0.75
	0.15	0.8287 (0.0263)	0.85	0.15	0.9305 (0.0124)	0.95
	0.20	0.8460 (0.0282)	0.90	0.20	0.9477 (0.0141)	0.95
8 deg/sec	0.05	0.5305 (0.0276)	0.50	0.05	0.5121 (0.02014)	0.50
	0.10	0.6414 (0.0343)	0.70	0.10	0.7218 (0.0273)	0.75
	0.15	0.7615 (0.0274)	0.80	0.15	0.8603 (0.0240)	0.90
	0.20	0.8586 (0.0241)	0.90	0.20	0.9661 (0.0105)	1.00

Table 3: Response Time ANOVA by Pattern, Coherence, and Speed

	df	F	p
Pattern	1, 455	10.55	1.25e-3**
Coherence	1, 455	229.84	<2e-16***
Speed	1, 455	0.149	0.70
Speed: Pattern	1, 455	0.007	0.93
Speed: Coherence	1, 455	1.01	0.31
Pattern: Coherence	1, 455	7.60	6.09e-3**
Speed: Pattern: Coherence	1, 455	0.001	0.97

Table 4: Percent Correct ANOVA by Pattern, Coherence, and Speed

	df	F	p
Pattern	1, 471	9.94	1.72e-3**
Coherence	1, 471	423.42	<2e-16***
Speed	1, 471	3.26	0.07
Speed: Pattern	1, 471	2.73	0.10
Speed: Coherence	1, 471	0.05	0.83
Pattern: Coherence	1, 471	19.48	1.26e-5***
Speed: Pattern: Coherence	1, 471	1.50	0.22

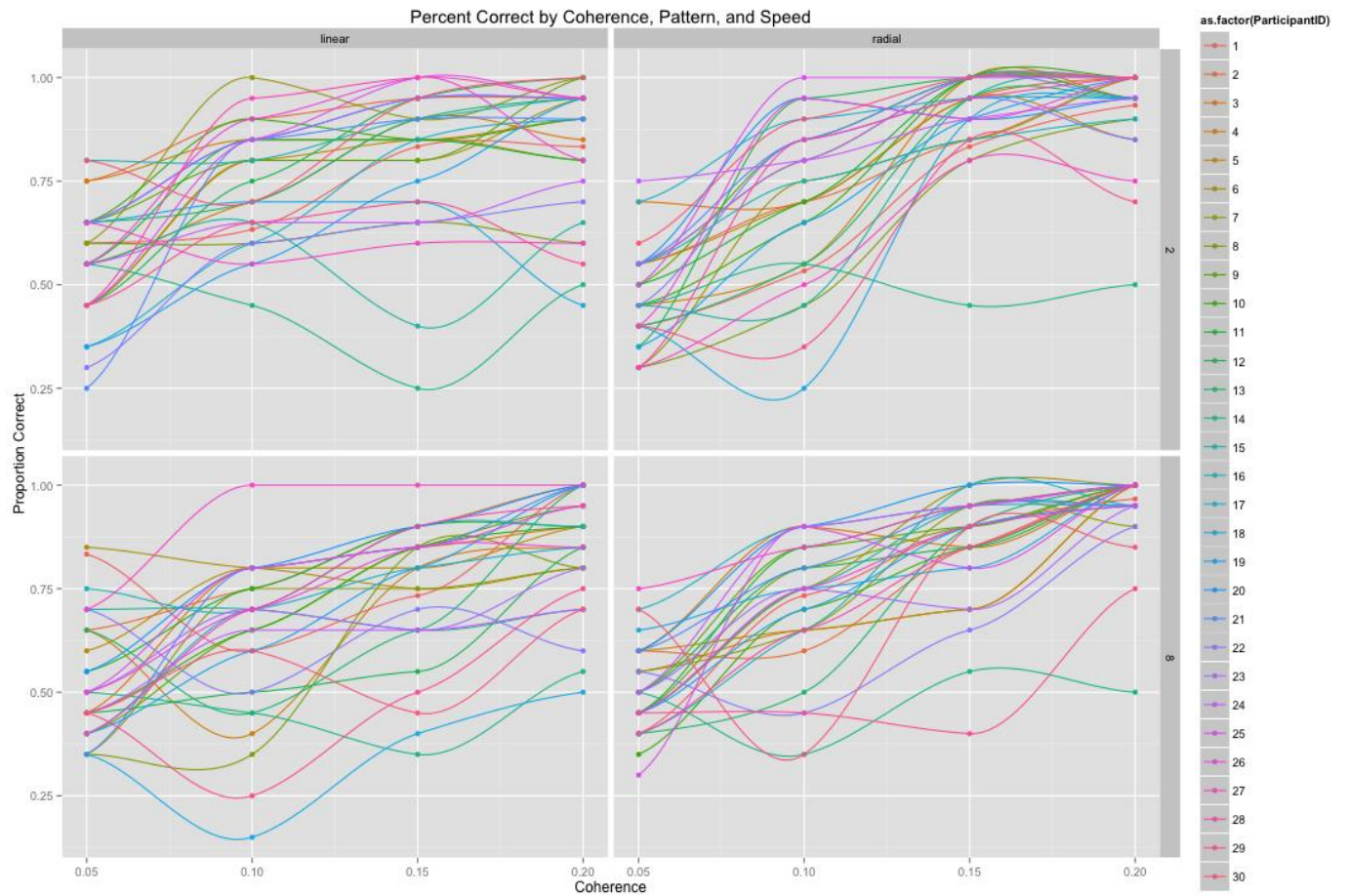


Figure 3: Graph of Individual Percent Correct by Coherence, Pattern, and Speed

Main effect of coherence, $F(1, 471) = 423.42, p < 2e-16$, shown by increase in percentage correct at higher coherence levels. Main effect of pattern, $F(1, 471) = 9.94, p = 1.72e-3$, shown by higher success rate to radial (right) than to linear (left). No main effect of speed, $F(1, 471) = 3.26, p = 0.07$, shown by no significant differences in success rates for 2 deg/s (top) and 8 deg/s (bottom). Interaction found between pattern and coherence, $F(1, 471) = 19.48, p = 1.26e-5$, shown by steeper increase for radial (right) than linear (left).

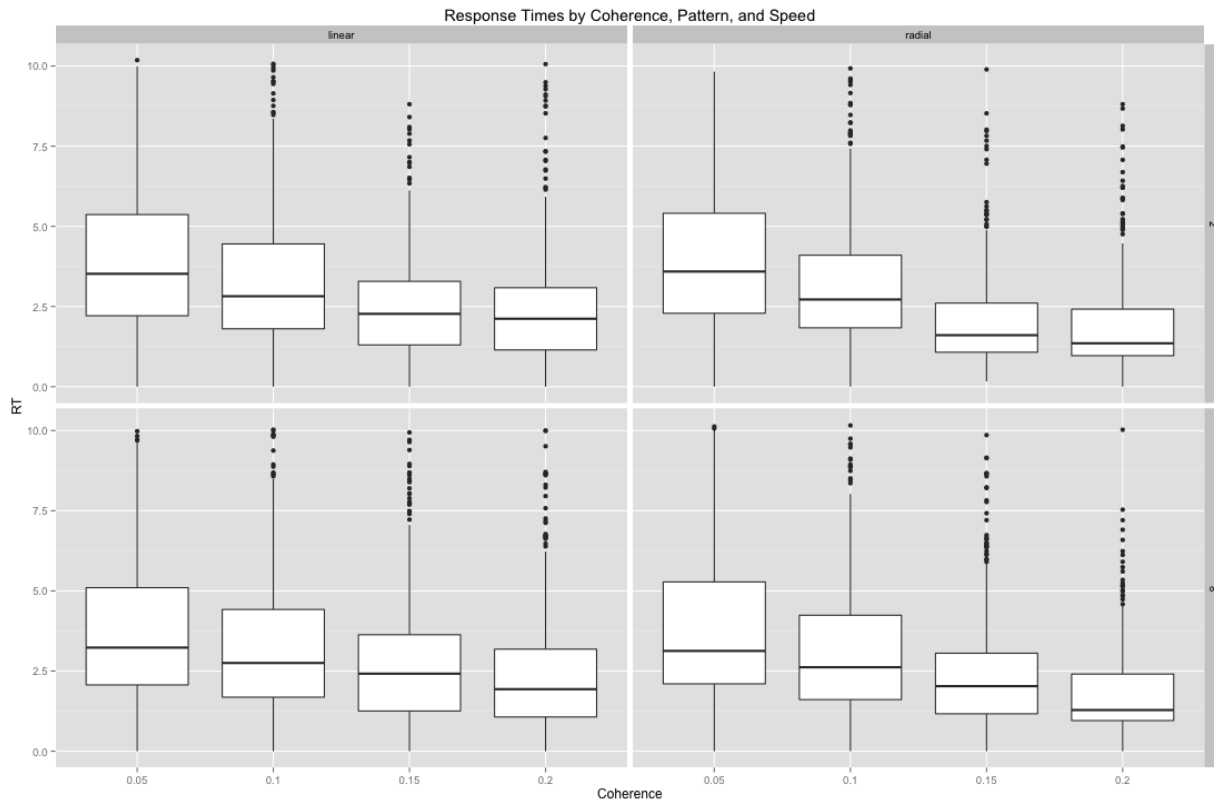


Figure 4: Box Plots of Response Times by Coherence, Pattern, and Speed

Main effect of coherence, $F(1, 455) = 229.84, p < 2e-16$, shown by lower response times at higher coherence levels. Main effect of pattern, $F(1, 455) = 10.55, p = 1.25e-3$, shown by lower response times to radial (right) than to linear (left). No main effect of speed found, $F(1, 455) = 0.15, p = 0.70$, shown by no significant differences in response time between 2 deg/s patterns (top) and 8 deg/s patterns (bottom). Interaction found between pattern and coherence, $F(1, 455) = 39.27, p = 3.85e-10$, shown by a steeper decrease in response times across coherence levels for radial than linear flow patterns.

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ACADEMIC VITA
William Adamiak
wadamiak311@gmail.com

EDUCATION

The Pennsylvania State University, Schreyer Honors College

Eberly College of Science

Major: Biology-Neuroscience Option

Minor: Psychology

University Park, PA

Graduation: May 2015

Dean's List

National Society of Collegiate Scholars Member

Devon Preparatory School

High School Diploma

National Honors Society and Spanish Honors Society Member; AP Scholar

Devon, PA

Graduation: June 2011

GPA: 4.15/4.00

PROFESSIONAL EXPERIENCE

The Princeton Review

SAT and MCAT General Chemistry Instructor

- Certified to teach both SAT courses and General Chemistry for MCAT prep courses
- Developed and taught unique lessons to engage students in learning how to master prospective material and to take the tests

University Park, PA

Summer 2014-Present

Pennsylvania State University Brain Development Laboratory

Undergraduate Researcher

- Worked with participants of all ages to collect data pertaining to motion processing in the brain
- Learned basics of low density and high density electroencephalography(EEG) including net application, data collection, and data analysis
- Currently working on honors thesis "Adult Observer's Sensitivity to Optic Flow Varies By Pattern and Speed" which will be presented at the Vision Sciences Society 2015 Conference

University Park, PA

Fall 2013-Present

Dr. Tracy Langkilde

Undergraduate Researcher

- Learned various laboratory data collection techniques pertaining to ecological field work
- Gained experience in various laboratory techniques like using a dissecting microscope, biomassing, etc.
- Attended and helped lead weekly undergraduate researcher meetings in the lab

State College, PA

Fall 2012-Spring 2013

Adamiak Family Partnership

Landlord's Assistant

- Worked to maintain 100+ apartment units in northern New Jersey and New York that were built and maintained by my grandfather over the past 60 years
- Developed skills in electrical work, painting, plumbing, tiling, masonry, apartment turnovers, landscaping etc.
- Strengthened social skills through constant interactions with tenants

Ridgewood, NJ

Summers 2010-2012/ Winter 2011

LEADERSHIP EXPERIENCE AND ACTIVITIES

Alpha Epsilon Delta Premedical Honors Society

National Member Beta Chapter

- Attended biweekly meetings featuring various speakers including physicians, psychiatrists, etc.
- Raised money for THON and helped collect for PSU- MSU blood donor challenge

University Park, PA

January 2014-Present

Schreyer Honors College Student Council

Member

- Attended and contributed to weekly meetings to discuss plans and events with other members
- Helped plan and execute events like the SHC Date Auction and Blood Drive

University Park, PA

Aug 2011 - Present

Leadership Training Program

Counselor

- Counseled 4th to 7th grade boys in after school program organized by the Legionaries of Christ
- Organized after school sporting events and conducted activities designed to educate the kids on being a leader and the value of other virtues like honesty, bravery, and faith.
- Capitalized on rewarding experience, honing leadership abilities to be prepared for future positions of leadership

Paoli, PA

2006-2009