Flash LAG Effect Model Discrimination

Stephen R. Gabbard

Wright State University

Follow this and additional works at: http://corescholar.libraries.wright.edu/etd_all

Part of the Industrial and Organizational Psychology Commons

Repository Citation

FLASH LAG EFFECT MODEL DISCRIMINATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

By

STEPHEN REA GABBARD

M.S. Wright State University 1994
M.B.A. Jacksonville University 1984
M.E.Ch.E. Clemson University 1981
Honors B.A. Rollins College 1975

2013
Wright State University

Scott N.J. Watamaniuk, Ph.D. Dissertation Director

Scott N.J. Watamaniuk, Ph.D. Graduate Program Director

Debra Steele-Johnson, Ph.D. Chair, Department of Psychology

R. William Ayres, Ph.D. Interim Dean, Graduate School

Committee on Final Examination

Valerie Shalin, Ph.D.

Alan Nagy, Ph.D.

Robert Patterson, Ph.D.
Abstract

Gabbard, Stephen R., Ph.D., Human Factors and Industrial/Organizational Psychology Ph.D. Program, Department of Psychology, Wright State University, 2013. Flash Lag Effect Model Discrimination.

The purpose of this study was to test the various models describing the Flash Lag Effect (FLE). Beginning with the initial work of Nijhawan (1994), several models have emerged endeavoring to explain the FLE (e.g., Eagleman & Sejnowski, 2000; Whitney, 2000; Baldo & Caticha, 2005). Two series of studies comprising 11 separate experiments were undertaken to differentiate these models, with a particular focus on the neural network model of Baldo and Caticha (2005). The experiments included the three primary FLE experimental paradigms: continuous motion (CM), flash-initiated (FIC) and flash-terminated (FTC). Ninety-three participants made observations in these three paradigms using a 2-AFC interleaved staircase protocol. ANOVAs were performed on each of the 11 experiments to determine main effects and interactions of the experimental factors, and additionally, overall FLE levels irrespective of factor influences. The combination of results shows that the neural network model (Baldo & Caticha, 2005) holds promise to form the basis for a unifying theory, whereas the postdiction (Eagleman & Sejnowski, 2000) and differential neural latency (Whitney, 2000) models do not. Implications and directions for further study are discussed.
Contents

Flash Lag Effect Model Discrimination ................................................................. 1
   Interactions of position determination and motion processes ............................ 5
   The Flash Lag Effect ......................................................................................... 10
   Flash Lag Configurations .................................................................................. 11
   Generalized Interaction of Motion upon Position Determination ..................... 13
Theories Explaining the Flash Lag Effect .............................................................. 15
   Motion Extrapolation ......................................................................................... 20
   Differential Neural Latency ............................................................................... 23
   Postdiction ........................................................................................................... 26
   Motion Bias .......................................................................................................... 27
   Attention ............................................................................................................. 29
   Facial Chimera Anomaly .................................................................................... 30
   Foveopetal / Foveofugal anisotropy ................................................................... 31
   Neural Computational Model .............................................................................. 32
Neural Net Model Predictions in FIC ................................................................. 35
Hypotheses and Research Questions .................................................................... 37
   Hypothesis 1 ....................................................................................................... 37
   Hypothesis 2 ....................................................................................................... 37
   Hypothesis 3 ....................................................................................................... 38
   Hypothesis 4 ....................................................................................................... 38
   Hypothesis 5 ....................................................................................................... 38
   Hypothesis 5a ..................................................................................................... 39
   Hypothesis 6 ....................................................................................................... 39
   Research Question ............................................................................................. 40
Narrative Summary of Experimental Series and Outcomes ................................. 41
Experiments ........................................................................................................... 42
   General ............................................................................................................... 42
   Experimental Series 1 ....................................................................................... 43
Apparatus - General ........................................................................................................... 44
Procedure - General........................................................................................................... 44
Experiment 1 – Reaction Time ......................................................................................... 45
Experiment 2-L: Continuous motion FLE 1 – (CM1) ...................................................... 46
Experiment 2-L: Continuous motion FLE 2 (CM2) ......................................................... 49
Experiment 3-S: Flash-initiated FLE – spatial (FIC-S) ................................................... 50
Experiment 3-T: Flash-initiated FLE-temporal (FIC-T) .................................................. 51
Experiment 4-S: Flash-terminated FLE-spatial (FTC-S) .................................................. 52
Experiment 4-T: Flash-terminated FLE-temporal (FTC-T) .............................................. 53
Preliminary Data Analysis Series 1 .................................................................................. 54
Transition from Experimental Series One to Series Two ................................................ 55
Experimental Series Two Description ............................................................................. 58
General Apparatus ........................................................................................................... 59
Procedure for Experiment Series 2 .................................................................................. 59
Procedure - General ........................................................................................................... 60
Experiment 1 – Reaction Time ......................................................................................... 61
Experiment 2-L: Continuous Motion FLE 1 (CM1) ......................................................... 61
Experiment 3-S: Flash-Initiated FLE – Spatial (FIC-S) ................................................... 62
Experiment 3-T: Flash-Initiated FLE-Temporal (FIC-T) .................................................. 64
Experiment 4-S: Flash-Terminated FLE-Spatial (FTC-S) ................................................. 65
Experiment 4-T: Flash-Terminated FLE-Temporal (FTC-T) ............................................ 66
Data Analysis ................................................................................................................... 67
Results Experiment Series 1 ............................................................................................ 68
Experiment 1 – Reaction Time ......................................................................................... 68
Experiment 2-Sp Continuous Motion FLE 1 – (CM1) ...................................................... 69
Experiment 2-L – Continuous-Motion FLE 2 (CM2) ....................................................... 70
Experiment 3-S: Flash-Initiated FLE – Spatial (FIC-S) ................................................... 71
Experiment 3-T: Flash Initiated FLE-Temporal (FIC-T) .................................................. 75
Experiment 4-S – Flash-Terminated FLE-Spatial (FTC-S) ................................................. 76
Experiment 4-T: Flash-Terminated FLE-Temporal (FTC-T) ............................................ 78
Results Experiment Series 2 ............................................................................................ 79
<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>The basic Flash Lag Effect. On the left side, the flash is coincident with a moving object when it flashes. The right side illustrates what an observer typically reports.</td>
<td>1</td>
</tr>
<tr>
<td>Figure 2</td>
<td>McGurk Effect courtesy of BBC two (<a href="http://www.youtube.com/watch?v=GLN8vWM3m0">www.youtube.com/watch?v=GLN8vWM3m0</a>). The left panel shows the man forming the letter “F”; on the right, he is forming a “B.” The listener will hear “Fah” or “Bah” despite the fact that the sound is “Bah” in both cases.</td>
<td>2</td>
</tr>
<tr>
<td>Figure 3</td>
<td>The hollow mask illusion. This is a frame grab from a video uploaded by LvDigitalPhotography, (<a href="http://www.youtube.com/watch?v=01LMFFpAWYM">http://www.youtube.com/watch?v=01LMFFpAWYM</a>). It shows the mask at an oblique angle. Note that the right half is actually concave to the viewer.</td>
<td>2</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Müller-Lyer illusion. The left line segment is seen by most people to be longer than the right segment.</td>
<td>3</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Peripheral drift illusion. Reading the surrounding text or alternately fixating random points within the graphic produce the perception of circular motion.</td>
<td>4</td>
</tr>
<tr>
<td>Figure 6</td>
<td>In this example, the center Gabor is moving rightward and the upper and lower patterns are static. In this case, the perception is that the center will be right-shifted.</td>
<td>6</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Flash lag effect – continuous motion condition (CM).</td>
<td>12</td>
</tr>
<tr>
<td>Figure 8</td>
<td>The left grouping shows the actual stimulus, with the fading gray bars depicting past positions. The right grouping shows the percept qualitatively, with the rotating bar misaligned with the flashing bars.</td>
<td>12</td>
</tr>
<tr>
<td>Figure 9</td>
<td>The blue circle is orbiting the fixation ‘x’ clockwise. It is blue most of the time, except for the yellow flashes. The left panel shows the actual stimulus as it reaches the “830” position and flashes yellow, and the right panel shows a stylized percept.</td>
<td>13</td>
</tr>
<tr>
<td>Figure 10</td>
<td>(From Khurana et al. 2006, p.2758). Participants are shown a moving-face half and a flashing-face half. For recognition of the face, actual alignment is better than FLE-compensated alignment, arguing that the parvocellular pathway may not participate in the FLE.</td>
<td>31</td>
</tr>
<tr>
<td>Figure 11-1</td>
<td>Each node in the input layer is connected to 5 nodes in the hidden layer. The hidden layer nodes each receive 5 inputs. The same connection pattern exists between the hidden and output layers. The weights are bilaterally symmetrical. Each vertical column represents a coded retinal position.</td>
<td>32</td>
</tr>
<tr>
<td>Figure 11-2</td>
<td>Panels A-E show the cascade of the neural net model as the light source moves from left to right across the retinal positions. The original input is in position 3 (flashlight in Panel A), whereas the first output (Panel E) is in position 4.</td>
<td>36</td>
</tr>
<tr>
<td>Figure 12</td>
<td>The three panels show stylized graphical outcomes from a staircase procedure. Panel A shows perfect responding, resulting in the minimum SD based on the last 6 points. Panels B and C have about the same SD (7 times A), and show both forms of instability of judgment. Experimental data exhibiting variants of B and C that produced 5x the minimum</td>
<td>67</td>
</tr>
</tbody>
</table>
SD were replaced as described in the text.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 13</td>
<td>The group average of the individual participants’ median, average, and top 5 reaction times. Error bars are ±1 standard error.</td>
<td>69</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Plot of delay vs. foveal approach, showing both significant difference between the levels of approach, and that the foveopetal condition is significantly different from zero. Error bars are ±1 standard error.</td>
<td>69</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Delay (more negative = greater FLE) as a function of flashing and moving stimulus luminance. Error bars are ±1 standard error. Note that the bright flash had a smaller FLE in both level moving stimulus luminance, nearing significance (p=.03).</td>
<td>71</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Means and S.E.s for each of the 8 conditions of Experiment 4. Offset is in deg. V.A. Of note here is that the data failed the homogeneity of variance tests.</td>
<td>72</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Effect of moving stimulus luminance on FLE in the FIC. Note that the higher luminance level produced a lower FLE, contrary to that predicted for the CM.</td>
<td>73</td>
</tr>
<tr>
<td>Figure 18</td>
<td>The 3-way interaction plot of luminance-luminance-foveal approach for the TOJ between the flashing and moving stimuli. This interaction is not significant ($F(1,12) = 5.66, p&gt;.01$), but the same interaction of unmodified data was significant at .01 ($F(1,12 = 10.7, p&lt;.01$), suggesting that this may warrant further investigation. This representation shows that the interaction between the luminance levels of the two stimuli reverses completely for the two foveal approach levels.</td>
<td>75</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Interaction plot showing offset as a function of luminance. This effect did not reach significance, but indicates a thread for future research.</td>
<td>76</td>
</tr>
<tr>
<td>Figure 20</td>
<td>This plot shows the significant main effects of moving luminance and foveal approach on the temporal perceptual precedence of the flashed vs. moving stimulus.</td>
<td>77</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Delay by condition. Error bars are 1 standard error. Compare bars 3 with 5 and 4 with 6, each pair separated by &gt; 2 std errors.</td>
<td>78</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Correlation and simple regression equation for FLE and simple RT data from Experiments 1 and 2.</td>
<td>81</td>
</tr>
<tr>
<td>Figure 23</td>
<td>Correlation and simple regression equation for only ‘positive’ FLE and median RT data from Experiments 1 and 2.</td>
<td>81</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Main effects and interaction plot of moving stimulus luminance and foveal approach collapsed across flashed stimulus luminance.</td>
<td>82</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Plot of FIC FLE. Both moving stimulus ‘bright’ levels have FLEs that are ‘not greater’ than the corresponding ‘dim’ levels FLEs, supporting hypothesis 2. Error bars are ±1 standard errors.</td>
<td>82</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Plot of FIC temporal delay by condition. The flash is seen first in all conditions. There were no significant luminance effects.</td>
<td>84</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Plot of FTC spatial offset vs. foveal approach. Error bars are ±1 standard error. There was no predicted dependence upon luminance, but the overall theme that the moving stimulus would be perceived to fall short of its physical endpoint was supported.</td>
<td>86</td>
</tr>
<tr>
<td>Figure 28</td>
<td>Plot of FTC temporal delay vs. luminance conditions. Error bars are ±1 standard error. The combination of a bright flash and dim moving stimulus appears significantly different from the other three combinations, but the omnibus F was not significant for any main effects or interactions. However, this is explained by the fact that the interaction between these factors approached significance at α=.01.</td>
<td>87</td>
</tr>
<tr>
<td>Figure 29</td>
<td>The left panel shows the linear regression between the foveofugal and foveopetal levels with all data included. Removal of the five apparently anomalous data points in the lower right of A yields the relationship shown in B with a much higher correlation.</td>
<td>88</td>
</tr>
<tr>
<td>Figure 30</td>
<td>Linear regression between foveopetal FLE and RT shows a significant positive relationship.</td>
<td>90</td>
</tr>
<tr>
<td>Figure 31</td>
<td>Histogram of individual condition results from Series 2, Experiment 2-L.</td>
<td>97</td>
</tr>
<tr>
<td>Figure 32</td>
<td>The panel on the left (A) shows the regression line for the 15 observers for Experiments 1 &amp; 2-L of Series 2. The panel on the right (B) shows the same data with the observer removed whose regression residuals exceeded 2.0. The $R^2$ on the left is .056 and nonsignificant. The $R^2$ on the right is .251 and approaches significance ($F(1,12) = 4.02, p = .068$). Negative FLE values are flash lag and positive values represent flash lead.</td>
<td>99</td>
</tr>
<tr>
<td>Figure 33</td>
<td>Data from Series 2, Experiment 3 FIC-S. FLE dependencies shown upon foveal approach and moving stimulus luminance.</td>
<td>100</td>
</tr>
<tr>
<td>Figure 34</td>
<td>FLE FIC-S. The smallest of the 4 conditions (collapsed across Flash luminance) is significantly greater than zero, making all conditions supportive of hypothesis 5, that there is a significant FLE under all luminance combinations.</td>
<td>111</td>
</tr>
<tr>
<td>Table 0</td>
<td>Summary of differences between Series 1 and 2</td>
<td>57</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------------------------------------------</td>
<td>----</td>
</tr>
<tr>
<td>Table 1</td>
<td>Summary of FIC FLE effects for foveal approach and moving stimulus luminance. ** Flash lead (t(14) = -2.92, p = .0112) * Flash lag (t(14) = 2.79, p = .0145)</td>
<td>74</td>
</tr>
<tr>
<td>Table 2</td>
<td>Summary of foveal approach results, all spatial experiments, both series.</td>
<td>102</td>
</tr>
<tr>
<td>Table 3</td>
<td>Summary of $I_{\text{flashing}}/I_{\text{moving}}$ interactions, all spatial experiments, both series.</td>
<td>105</td>
</tr>
<tr>
<td>Table 4</td>
<td>Summary of $I_{\text{flashing}}/I_{\text{moving}}$ t-tests, all spatial experiments, both series.</td>
<td>105</td>
</tr>
<tr>
<td>Table 5</td>
<td>Summary of FTC-Spatial experiments all statistical tests.</td>
<td>107</td>
</tr>
<tr>
<td>Table 6</td>
<td>Summary of FTC-Temporal experiments all statistical tests.</td>
<td>109</td>
</tr>
<tr>
<td>Table 7</td>
<td>Summary of FIC-Spatial FLE levels relative to 0 with Type I error managed using Bonferroni modified significance limits ($\alpha = .00625$).</td>
<td>110</td>
</tr>
<tr>
<td>Table 8</td>
<td>Summary of Series 2 FIC-Spatial FLE levels relative to 0 with Type I error managed using Bonferroni modified significance limits ($\alpha = .00625$).</td>
<td>112</td>
</tr>
<tr>
<td>Table 9</td>
<td>Summary of luminance level main effects and interactions for both FIC-S experiments (Series 1 and Aeries 2). Note that the interaction in Series 2 nears significance. The direction of the effect of this interaction is as expected (dim flash = reduction in moving stimulus luminance dependence).</td>
<td>113</td>
</tr>
<tr>
<td>Table 10</td>
<td>Summary of luminance level main effects and interactions for both FIC-T experiments (Series 1 and Series 2).</td>
<td>114</td>
</tr>
<tr>
<td>Equation 1</td>
<td>$\frac{dx_i(t)}{dt} = -\alpha_i x_i(t) + \alpha_i f(y_i(t))$</td>
<td>1</td>
</tr>
</tbody>
</table>
Glossary of Abbreviations, Definitions, Effects and Illusions

Abbreviations
FLE = Flash Lag Effect
CM = Continuous Motion {condition}
FIC = Flash Initiated Condition
   -S (Spatial); -T(Temporal)
FTC = Flash Terminated Condition
   -S (Spatial); -T(Temporal)
DNL = Differential Neural Latency
TOJ = Temporal Order Judgment
NN = Neural Network

Definitions
- Akinetopsia – Inability to perceive motion
- Anti-foveal – Edge or side of an object farthest away from the foveated point in the visual field
- Arc-minute (arc-min) – 1/60th of a degree of visual angle
- Arc-second (arc-sec) – 1/60th of a minute of visual angle
- Chimera – a split being or face, such as a minotaur with 2 or more distinct parts
- CPS – cycles per second
- Dorsal, Dorsal-Pathway – terminating in the parietal lobe it is considered the more primitive of the two visual systems (dorsal & ventral) that comprise the two-streams visual hypothesis and is responsible for ‘where’ and ‘how’ information
- Eccentricity – distance from the foveated position in a visual field; farther is more eccentric
- Extrastriate – literally outside the striate cortical area of V1, this area would include the medial temporal (MT) visual area responsible for resolving motion signals
- FLE Anisotropy – property of the flash lag effect wherein motion toward the fovea and motion away from the fovea produce different effect levels even if all other conditions are constant
- Hemifield – Half of the visual field. This can be left-right or upper-lower
- Flash Drag Effect – Flash Drag Effect – The mislocalization of a stationary object due to a proximate moving object
- Foveofugal – Motion away from the foveated position in the visual field
- Foveopetal – Motion toward the foveated position in the visual field
- Gabor – a sinusoidal contrast display whose edges are diffused with a Gaussian overlay
- Lateral Geniculate Nucleus (LGN) – Area in the visual neural pathway between the retina and the V1 area of the visual cortex (thalamus), separated into six layers (2 magnocellular and 4 parvocellular)
- Leaky Integrate and Fire (LIF) – A representation of a neuron with the additive properties of summing incoming neural signals over time while simultaneously leaking those signals
• Magnocellular – cells in the LGN receiving their signals from the larger M cells of the retinal ganglia and which are in the 2 ventral layers of the LGN and have finer temporal resolution than their parvocellular counterparts
• Motion Bias – an advancement of the earlier postdiction proposition wherein motion biases the process of determining position using an integration of position over a time window
• Parvocellular – cells in the LGN receiving their signals from the smaller P cells of the retinal ganglia and which are in the 4 dorsal layers of the LGN and have finer spatial resolution than their magnocellular counterparts
• Postdiction – the process of determining the position of a moving object where the process begins upon receiving a cue (e.g., flash) and continues over a finite integration time (estimated to be 80 ms)
• PSE – point of subjective equivalence; two stimuli are matched for some property where an observer judges them to be subjectively the same
• Reaction Time (RT) – the time it takes to respond to a stimulus such as a flash
• Retinotopic – the property of retinal organization wherein the cellular layout corresponds to the viewable physical space
• Saccade – the event where the eyes very quickly ‘jump’ to a new point in the visual field
• Spatiotemporal – a term used when spatial and temporal effects are combined such as happens when motion is involved
• Spreading Activation – the neural process wherein neurons adjacent to activated neurons are also excited in a cascade or omnidirectional spreading out
• Striate Cortex – deriving its name from its appearance when stained, this is the location of V1
• Ventral, Ventral Pathway – terminating in the temporal lobe it is considered the more evolutionarily recent of the two visual systems (dorsal & ventral) that comprise the two-streams visual hypothesis and is responsible for ‘what’ information
• Vernier – deriving its name from its inventor, a vernier is a precise measurement device that increases the precision of physical distance measures, generally by an order of magnitude

Effects and Illusions
• Fröhlich Effect – An effect whereby the initial position determination of a moving object that suddenly appears (as if from behind a screen) is displaced in the direction of that object’s motion
• Hess Effect – An effect where brighter (more contrast) moving stimuli are determined by observers to be farther ahead along their motion path than adjacent moving stimuli of lower contrast
• Hollow Mask Illusion – An illusion whereby the percept generated by looking at the back-side of a face-mask is convex (facing the observer) rather than concave (pushed in and away from the observer)
• McGurk Effect – An effect whereby the observer, when listening to two identical sounds will hear them differently depending upon the visual cue obtained from looking at the lips
• Motion After Effect (MAE) – Or waterfall illusion, is seen when after even a brief period of observing a continuously moving stream, a ‘backward’ motion is perceived when that moving stream is stopped
• Müller-Lyer Illusion – the misjudgment of the length of a segment based upon the cues given by the geometry of the rays emerging from the ends of the segment
• Peripheral Drift Illusion – An illusion whereby a static image of concentric circles made up contrasting segments appears to move due to the motion detecting cells being stimulated with retinal motion in such a way as to generate a motion percept
• Pulfrich Effect – An illusion of motion in depth brought about by the binocular temporal disparity brought about by the differential temporal delay induced by reducing the contrast monocularly
• Representational Momentum – A position mislocation induced by the overlay of representational physics on a static scene
Acknowledgments

The author wishes to thank his advisor and friend Scott N.J. Watamaniuk for his guidance, encouragement, and pragmatism in completing this work. He also wishes to thank Neena Zwier and Jennifer Saldanha, Scott’s lab assistants at the time of data collection for their help. The dissertation committee of Al Nagy, Robert Patterson, and Valerie Shalin kept the questions well framed, honest, and true to the nature of scientific exploration. Both John Flach and Debra Steele-Johnson, the two psychology chairs for whom the author worked during the last 16 months of this effort, were supportive of its completion.

Two additional people, not affiliated with Wright State, were instrumental in helping the author complete this dissertation. First, Dan Cullin who met virtually every week with the author offering insights and encouragement about the personal challenges associated with this kind of endeavor and second, but in no way last, was the author’s wife Christina. She patiently copy-edited this volume, a critical contribution by itself, but also and much more importantly allowed the personal space and freedom to take this on – and with no possibility that the work would ultimately be returned in the form of career rewards only to support her husband’s desire to do it.
Flash Lag Effect Model Discrimination

Motion detection and position determination are critical perceptual abilities that are extraordinarily well developed in humans. We use them constantly, sometimes consciously and purposefully, but most often passively and with no overt effort. Without these abilities, many critical and most mundane activities would be impossible or significantly impaired. We generally take the accuracy of these percepts for granted, because we have adapted so successfully to their use. In fact, the idiom or proverb of “seeing is believing” emanates from our fundamental confidence that we can trust what we see, and indeed often extends to the obverted contraposition of “we cannot believe what we cannot see.” We, as a species, maintain this, despite the countless illusion-based demonstrations to the contrary. The processes of visual perception are not fully understood, but what is known increasingly suggests that the sensation and interpretive perceptual processes are highly interactive across many neural levels (Schmolesky, 2007; Pollen, 2011). This interactivity establishes the possibility, even the probability, that perceptual interpretation can be dependent upon the states of other neural variables, i.e., that context matters (Adesnik, Bruns, Taniguchi, Huang, & Scanziani, 2012). Numerous demonstrations indeed show that context fundamentally changes what is perceived – clearly suggesting that perception necessitates some interaction between immediate sensation, concurrent sensation, and

![Figure 1. The basic Flash Lag Effect. On the left side, the flash is coincident with a moving object when it flashes. The right side illustrates what an observer typically reports.](image-url)
longer-term processes (e.g., Angelucci A. & Bressloff PC, 2006; Paradiso et al., 2006). This project explores one of the many illusions that seems to emanate from such interactions – the flash lag effect (FLE), an effect where the position of a flashed stimulus appears to lag spatially behind a moving stimulus with which it is coincident (Figure 1).

The McGurk effect (named after Harry McGurk of McGurk & McDonald, 1976) is a stunning example of the interaction of concurrent visual and auditory input. What you hear appears inextricably linked to what is seen. On the left side of Figure 2, the speaker is forming an ‘F’ with his lips and on the right, a ‘B’. The sound that is made is identical in both cases and sounds like a ‘bah,’ but inevitably you hear ‘fah’ when observing the lips move in the left image. Knowing the illusion does not help overcome the interpretation.

The hollow mask illusion is one example of how what one ‘knows’ about faces in long-term memory impacts the image interpretation (Hill & Johnston, 2007). When one observes a slowly rotating mask, the
interpretation is that the face projects out of the plane of the image. Figure 3 shows this illusion stopped at an oblique angle. There is only one mask present. The interior right part must be going in, as the mask is aimed left, but the perceptual interpretation is that it is a normal face projecting outward. Like the McGurk effect, knowing the illusion and even the science of the illusion does not allow one to see past it, although a recent study suggests that schizophrenics can see through it arguing a disconnect of top-down guidance to perceptual processes (Dima et al., 2009).

The Müller-Lyer illusion shows the interaction of context on the estimation of line segment lengths. The illusion is that the object on the left (Figure 4) appears to be longer. There have been several theories proposed to explain this, but according to Erlebacher and Sekuler (1969), although the theories differ in detail, they all share the notion that the non-line components (context) of the figures are perceptually grouped in the judgment of length. One interpretation is the scene-based theory arising from the imposition of 3-D context from a 2-D presentation (Redding & Vinson, 2010). The left object appears to be an interior corner and ‘away’ from the observer, whereas the right object appears to be an exterior corner, projecting toward the observer. Since something in the distance that is the same height as something closer to the foreground must be taller, we perceive it as such. Getting out one’s ruler and verifying that the lines are the same length does not allow one to ‘see through’ the illusion – they are perceptually different in length. However, this explanation cannot extend to other Müller-Lyer
configurations such as the dumbbell and eyeglasses versions that do not have the same 3-D analogs. However, even those versions contextualize the lines differently, supporting the general argument that perceptual context matters.

Many complex patterns seem to induce the perception of motion where there is none. The example in Figure 5 is a complex pattern of concentric contrasting segments that somehow stimulates motion detectors and is classified as a peripheral drift illusion (PDI) first identified by Fraser and Wilcox (1979). This illusion’s trick is that observers have a tendency to make saccadic eye movements to various locations within the object or in the neighborhood of the object such as when reading text nearby. The pattern of contrasting segments has a spatial frequency that is varied and will have differential interaction with saccadic translations. Simple motion detectors are activated because of the phase relationship between the translation and the illuminated segment. This explanation is supported by the cessation of the effect when one fixates on the center of the image and the motion stops (Faubert & Herbert, 1999). Nevertheless, this reliable percept shows a relationship between a static complex grating-like image, linear eye movements, and rotational motion percepts that are generally attributable to visual areas well beyond V1. These and countless other

Figure 5. Peripheral drift illusion. Reading the surrounding text or alternately fixating random points within the graphic produce the perception of circular motion.
demonstrations argue strongly that perceptions, including motion perceptions, can be fundamentally affected by context.

Representational momentum (RM) is a phenomenon wherein a still scene imparts a set of physics-driven motion and position cues (Freyd & Finke, 1984). When the scene depicted clearly appears to have implied follow-on motion (e.g., an object in the process of tipping or falling), observers will state that the object was in a position indicated by the continuation of the represented momentum. This is clearly a phenomenon where a cognitive overlay is reflected in a reported percept. When a flash was added to an RM paradigm that compared upward and downward motion, the downward motion only of a leg of a rotating bar had the RM effect significantly increased at a rotational speed of 50°/s (Munger & Owens, 2004). At 100°/s and 150°/s, however, the increase in the RM effect was seen in both upward and downward directions. In RM paradigms, gravity appears to enhance the effect of RM motion elements under some conditions. It would appear from these results that at the lowest speed, the ‘gravity’ factor is applicable. At the higher speeds, it appears that the rotating stimuli are no longer affected by gravity (like a spinning propeller). The fact the RM is enhanced by the FLE argues for some level of additivity and thus interaction between a cognitive process and one that is generally reported as being perceptual.

**Interactions of position determination and motion processes**

Humans have remarkable vernier acuity. The theoretical optical resolution limit, based on the pupil diffraction of the eye, is about 24 arc-seconds (0.4 arc-min), which corresponds to approximately the minimum cone spacing in the fovea. Vernier acuity, measuring how well we can align lines is 3-fold better (~ 8 arc-seconds) than this best
possible case, and about 5-fold better than the best practical vision. This ability, which is
dependent on conditions such as luminance and exposure time, argues that our ability
transcends optics and foveal grain using some neural mechanism beyond the retina

(Westheimer, 1975). DeValois and DeValois (1991) examined vernier alignment bias (dc
offset) using a vertically arranged set of
moving Gabor patches, similar to those
depicted in Figure 6. The white dot in the
figure is the fixation point. The motion of the
gratings created a directionally sensitive
perceptual misalignment of the middle patch
compared to the reference patches above and
below it, using a 2-AFC position decision
protocol with a method of constant stimuli.

The strong inference is that motion was altering the perception of position in some way.

They found that there was a consistent shift in the perceived position of the central square
in the direction of the drifting gratings from 2 arc-min to 16 arc-min depending upon
spatial (highest at 1 c/deg and lowest at 4 c/deg) and temporal frequencies (highest
between 4 Hz and 8 Hz) and eccentricity from the fixation point. Increasing eccentricity
from zero (foveated) to eight degrees linearly increased the size of the effect. Bias and
temporal frequency positively covaried up to 4 Hz. DeValois and DeValois suggested
that this bias might be compensatory for the perceptual lag of between 50 ms and 100 ms
before a stimulus registers in the striate cortex. They also determined that movement
toward or away from the fovea produced a larger effect than one moving tangentially. This is significant in that it argues that the areas of the visual cortex involved in the FLE may not necessarily include those involved in the perception of circular trajectories.

Chung, Patel, Bedell, and Yilmaz (2007) replicated aspects of the DeValois and DeValois (1991) experiment deepening the examination of the dependence upon spatial and temporal frequencies, carrier velocity and adding exposure time as a variable. Important to the present study is that the magnitude of the effect was confirmed. Additionally, they also illustrate a mechanism that differentiates the gain on the leading and trailing edges of drifting stimuli. They propose that gain and attenuation signals are related to the rate of luminance change of the carrier in a drifting Gabor. This means that on the attack side there is excitation and on the decay side there is attenuation. This attenuation is posited to be related to the suppression of formerly occupied positions in order to de-blur motion. This may be related to a particular observation that is discussed in the flash lag configurations section, when the flash is shown inside a moving annulus.

The Hess effect shows the impact of differential luminance on relative position determination in moving objects (Williams, 1980). If two aligned objects translate across the visual field, the brighter of the two will appear ahead of the dimmer one. Given that in a static presentation they would be aligned, the perceptual misalignment must be an interaction between motion and luminance difference as the targets move across the visual field. A reasonable conclusion is that because each retinal area is illuminated only briefly and there is a luminance dependence on position perception, there must also be luminance dependent differential response latency in the visual system. Maunsell and Gibson (1992) showed that parvocellular lesions in the lateral geniculate nucleus showed
no impact on response latency to V1 in macaques, whereas magnocellular lesions retarded responses by 7 ms to 10 ms. Shapley and Victor (1978) showed that in cat retinal ganglia, neurons projecting to the magnocellular region were activated before those projecting to the parvocellular region for high-contrast stimuli. This certainly gives a plausible physiological explanation for a high-contrast target to be processed more quickly than a low-contrast target and could explain the Hess effect. A 10 ms advantage would result in a 12 arc-min advantage to a high luminance (contrast) targets moving at 20 °/s. However, Williams (1983) measured the Hess effect across a wide range of contrasts on analog (mechanical) equipment and obtained high-contrast advantages as high as 80 ms. Even though these data are from macaque monkeys, it would appear that more than the contrast difference contributions of the magnocellular and parvocellular systems are at work to produce such a large effect size.

In 1872, Herr Professor Mach presented findings from his assistant Vinko Dvořák where a stereoscopic presentation to fixated retinas was displaced temporally by phase-shifting rotating stimuli observed through slits. The temporal displacement produced an artificial depth illusion that is now known as the Mach-Dvořák effect. The Pulfrich illusion produces a similar depth illusion by using disparate neutral density filters. Placing a filter over one eye (reducing the luminance) will create an apparent elliptical path for a swinging pendulum (Mojon, Zhang, Oetliker, & Oetliker, 1994). By equating effect size in a series of within-subjects psychophysical comparisons, Mojon et al. were able to equate the temporal displacement of the Mach-Dvořák effect with the effective delay produced by the neutral-density filters of the Pulfrich effect. The effect is about 25 ms for a neutral-density filter with 2% transmission and 8 ms for one with 20%
transmission. These results are thematically similar to the Hess effect wherein
differential luminance produces differential position perceptions with moving stimuli.

The Fröhlich effect shows that a moving object that suddenly appears will be
displaced in the direction of its motion. This effect has no observable spatial reference –
an observer must simply indicate the position that the stimulus was first observed, and
would be measured in optical angle of error (Aschersleben & Müseler, 1999). The
question for this phenomenon is whether the stimulus is simply unseen initially, perhaps
due to an attention effect (Hubbard & Motes, 2005), or whether the entire percept is
spatially shifted based on some other mechanism. For a stimulus that is invariant, a
displacement does not distinguish between these mechanisms. Cai (2003) used color and
size variations in the initial few frames of presentation to show that the initial conditions
of the stimulus are indeed perceived; the stimulus is simply seen as spatially displaced.
In this case, it could simply be that the parvocellular system responsible for color makes
reporting the color change possible, as there is no position-report task consequence to the
color report delay. The significant point of the Cai study is that initial features of the
target are not lost, the entire target is simply displaced – there is no ‘onset blink’ that
masks all of the target’s features. This distinction is critical to the understanding of the
phenomenon and models that endeavor to explain it.

Collectively these phenomena show that the flash lag effect is not nearly an
isolated case of interactions between dissimilar stimulus types. Indeed, one might even
predict an FLE of some degree given the perceptual displacements of both stationary
stimuli, as in the DeValois and DeValois (1991) work on moving Gabors, and moving
stimuli, such as in the Fröhlich effect.
The Flash Lag Effect

In its most basic form (Figure 1), the FLE is exhibited when an observer, while fixated on a stationary target, is presented with a stimulus that is translating across the visual field. At some point along its path, a second stimulus is briefly flashed while aligned with the moving stimulus. For digital renderings, the flash is typically a single video frame. The flashed stimulus acts as both a spatial and temporal marker. The observer will reliably report that at the time of the flash, the moving stimulus was beyond the position of the flashed (now lagging) stimulus along its projected trajectory. Circular motion paths render the same qualitative results as does linear motion. The estimate of the lag is generally made by manipulating the timing of the flash to create perceptual alignment and comparing that to veridical alignment, measured either spatially (subtended degrees of separation) or temporally (ms of flash timing). There are numerous variations of the paradigm, often introduced to support one of the theories that have been proffered to explain it.

A significant interest in this phenomenon was taken subsequent to its reintroduction into the motion perception literature by Nijhawan (1994). In this brief letter, he posited that the FLE resulted from the same neural compensatory process involved in allowing, as an example, veridical spatial positioning of a hand for purposes of catching a ball. The neural transmission lag must be, in this view, compensated for to achieve intercept accuracy. He argued that there could be some extrapolative process or mechanism that allowed for proper spatial positioning, even though there would be a delay in the order of 100 ms in the perceptual apparatus. In an effort to explain this compensation, Nijhawan further posited that there is a neural processing advantage of the
moving element compared to the unpredictably timed flashed element. He reported an FLE of 82 ms in one of the numerous FLE experimental paradigms that would ensue, adding plausibility to his arguments.

The FLE was earlier described, although not named as such, by Mackay (1958). In his study (purposefully not referred to as an experiment per se), 50 participants observed that constantly glowing objects (vacuum tubes) were observed to move differentially and ahead of objects that were illuminated by a stroboscope when the eye was artificially moved using a finger. This illusion was dependent upon the frequency of the stroboscope, with the effect being well observed at 5-6 cycles per second (cps) and not at 15 cps or more. The participants described that the tubes were ‘ahead’ of the intermittently illuminated objects and that it took several flash cycles for the lagging objects to ‘catch up’. Hence, the flashing objects were ‘lagging’ the constantly lit moving objects. Nijhawan’s initial explanation would fit the observations made by Mackay. This rather straightforward and neurologically plausible mechanism would not be as successful for other FLE configurations, and additional theories and mechanisms have subsequently been proposed to explain them. However, before discussing the FLE further, a deeper discussion of the main types of experimental configurations is required.

**Flash Lag Configurations**

In the simplest configuration (Figure 7), a translating object crosses the vertical position of the flashed object but at a different elevation. The flashed object generally persists for duration of a single video frame and is aligned with the position of the moving object at that time (a 60-Hz presentation would be aligned for 16.67 ms). As the moving object moves from one side of the flashing object’s position to the opposite side
at constant velocity, this configuration is referred to as the continuous-motion condition (CM). As depicted in Figure 7, the typical observer percept at the point of the flash is that the flash lags the moving object. Quantitative measurement is made by delaying the flash timing until the observer perceives subjective equivalence, and this is reported in milliseconds directly from the flash delay, or converted to optical angle of separation. Importantly, this configuration can be modified from the CM paradigm described above to one where the motion is initiated with the flash (Flash-Initiated Condition, or FIC). It can also be set up such that the flash terminates the motion (Flash Terminated Condition, or FTC). Essentially these are the first half (FIC) or second half (FTC) of the flash-related events in the CM.

![Diagram of flash lag effect – continuous motion condition (CM).](image)

The second configuration differs in motion pattern, but is otherwise quite similar to the first in terms of percept and quantification. A central bar is rotated (as a propeller blade). The fixation point is the center of the rotating bar or arc swept by it. At a random
position eccentric to the swept arc, a pair of lines is flashed that are 180° apart just as the rotating bar is aligned with them. Figure 8 shows a typical rotating bar configuration (Lim & Choe, 2008). If the gaze is fixed at the center of the rotating bar, the percept is as in (b), but if the gaze pursues the end of the bar, it is seen veridically with the flashed bars aligned with the moving one.

The third configuration (Eagleman & Sejnowski, 2000) is similar in that it has an orbiting stimulus (Figure 9), but in this case, the flash is contained within and concentric to an annulus. Again, when fixating the ‘x’, an observer will perceive the right panel when presented the left panel. The right side of Figure 9 shows a characteristic ‘collapse’ of the interior yellow stimulus into a ‘football’ shape. Noteworthy is the lack of extension of the interior yellow outside the circle. It is possible that the previously discussed theory by Chung et al. (2007) where trailing-edge suppression is seen in drifting Gabors explains how the stimulus that would be exterior to the circle is effectively erased, creating the shown percept. In effect then, the annulus appears to suppress the interior ‘dot’.

**Generalized Interaction of Motion upon Position Determination**

The FLE is specifically concerned with the perception of relative positions of moving and stationary stimuli and specific theories regarding that phenomenon will be discussed in the next section. Here, some experimental findings on motion’s impact on
position determination are briefly presented as context for the subsequent FLE discussion.

Whitney (2002) categorizes the theories emerging to explain the effect that motion has upon position as broadly temporal or spatial. In other words, the speed (timing) of encoding could affect position determination, or motion could directly affect positional encoding. The Hess and Pulfrich effects discussed previously appear to be temporal in nature, owing to the differential perceptual speed of dimmer versus brighter stimuli. The Gabor patches used, on the other hand, by DeValois and DeValois (1991), had neither real motion nor differential luminance to account for the positional shift.

With these three examples, it would appear that different mechanisms might be in effect for different circumstances, or that there is a more complex convolution of spatial and temporal properties to explain each as special cases of a more general theory.

Nishida and Johnston (1999) used a motion after effect (MAE) paradigm to determine that MAE biased a positional determination. They also showed that the time courses (onset and decay ramps) of the MAE and positional bias were non-congruent – and that the positional bias remained beyond the extinction of the MAE. This, they argue, dissociates the motion mechanism from the spatial mechanism. It should be noted that there were three observers in this work (two authors plus one naïve observer), and that the naïve observer’s results differed from the authors in that the effect decay rates were congruent, casting some doubt as to the veracity of these results. However, the generalized effect of MAE upon position was also observed in a linear motion paradigm (Snowden 1998). In this case, a most interesting non-linearity was reported, with the maximum positional displacement obtained at speeds between 10°/s and 15°/s, declining
to no effect at 32°/s. This could argue that only certain speed-selective neurons are involved in the position bias mechanism.

Mussap and Prins (2002) extended the findings of DeValois and DeValois (1991) by using coherent and non-coherent fields of dots. The position of an envelope of non-coherent dots was affected by the coherent motion of a relatively distant set of dots that could be considered as ‘global motion.’ This argues that the middle temporal (MT) area’s computation of global motion can affect the perception of the position of targets not positionally superimposed on the global motion generator. Whitney and Cavanaugh (2000) showed that position perceptions were displaced by stationary envelopes containing drifting gratings across distances up to 60°. Most interesting here was that rotating gratings had impacts that were eccentricity independent while the effects of linearly drifting gratings had an exponential decay, and extinguished by about 35°. Given that rotating motion and linear motion are independently processed, it could be argued that separate effectors are operating, depending upon what motion area is active.

**Theories Explaining the Flash Lag Effect**

Since 1994, when Nijhawan brought the FLE into focus for a new generation of psychologists and vision scientists, there have been many investigations into the various forms of the effect and several theories endeavoring to explain it. Despite these efforts, there has not yet been an explanation posited that has satisfied either the researchers involved in the FLE or explained all of the data. One reason for the explanatory flux is that there are many experimental result variations, and many of the result sets are consistent with more than one theory. Another is that some of the theories are able to explain some of the results, but not others. It is plausible, perhaps even likely, that there
are multiple competing perceptual phenomena occurring and that specific experimental configurations tend to emphasize different ones, leading to disparate experimental results. Furthermore, the effect has a temporal domain under 100 ms making precise measurements of it difficult, particularly with computer-generated stimuli with 12 to 20 ms screen refresh times. Finally, virtually all of the experimental results have small $n$ designs. Many of the experiments have the author(s) as observer(s), along with other laboratory members or naïve observers. The individual differences among the observers are often notable. For example, an experiment among a convenience sample of soccer referees and non-referees (psychologists) that included the authors showed significant results between subject groups, but also showed strikingly different results under some conditions among individual participants (Gabbard & Watamaniuk, unpublished). The comparative observational expertise of the authors was clearly in evidence, as theirs were the top accuracies among the seven observers. Kreegipuu and Allik (2003) also noted that the FLE is highly variable among observers. This calls into question whether different psychophysical phenomena are needed to explain the disparate FLE results, or whether some of the differences are simply artifacts of the sampling error brought about by small $n$ designs.

While the FLE is interesting in itself, its importance is made clear by Krekelberg (in Nijhawan, 2007) referencing his own work (Krekelberg & Albright, 2005) with macaque monkeys. The neural pathway from the retina to the motor cortex must travel at least from the photoreceptors to V1 via bipolar cells, retinal ganglia, and the lateral geniculate nucleus (LGN). This takes about 40-70 ms (Nijhawan, 2008). Beyond that initial feedforward mechanism to stimulate V1, higher processing in the middle temporal
area (MT) and the medial superior temporal area (MST), and resultant responses in the motor cortex, add additional delays. In the 2008 Beijing Olympic Games, the mean reaction time (RT) to the starter’s ‘gun’ for a sprint was 168 ms (95% CI = 160 ms – 178 ms) for men and 191 ms (95% CI = 180 ms – 205 ms) for women with a floor of 124 ms and 130 ms respectively. Kosinski (2010) reports that for college-aged participants mean RTs are 160 ms for sound and 190 ms for light sources. Bellis (1933) reported that the mean key-press time to a light stimulus was 260 ms for females and 220 ms for males. Therefore, it take about 200ms beyond the arrival at V1 (at between 40 ms and 70 ms) for most people to physically react. World-class athletes would appear able to react faster, though to auditory stimuli. Even taking into account the auditory channel’s speed vs. visual stimuli, the fastest athletes appear to be perhaps as quick as 120 ms additional beyond V1. For species with intercept capability to be successful, there must be compensation for these delays somewhere in the path from vision to motor response. This compensation could happen within the visual system, the motor system, or some combination thereof. It is possible that this phenomenon is the temporal equivalent of the prism spatial adaptation mechanism. Subjects, when given prism glasses that create a spatial offset, will initially miss the target in simple pointing tasks, but adapt quickly (within a few trials) using a cognitive strategy to minimize pointing error (Redding & Wallace, 2006). However, they will also realign their spatial maps to minimize the error permanently and effortlessly, as evidenced by the rebound error effect upon removing the glasses. Given that this adaptation is rapidly reached in active tasks and not in passive tasks, it seems that the mechanism for adaptation may be more of a dorsal path process than ventral (Mikaelian & Held, 1964). That this happens is unequivocal; where it
happens is not. Thus, the study of a phenomenon that shows a differential visual response between a moving stimulus and flashed stimulus could provide some insights about this compensatory mechanism. Krekelberg and Albright (2005) determined that this compensation does not happen in the dorsal-pathway MT because the latency of a single cell’s response to a randomly moving stimulus is, on average 45ms, which is similar to the known time it takes for a signal from the retina to reach the same area (40-70 ms).

The dual visual pathway structure (dorsal stream for action – ventral stream for perception) was proposed by Mishkin and Ungerleider (1982), based upon extensive anatomical study. Milner and Goodale (1995) comprehensively tested patient Dee, who had undergone an anoxia event with very specific brain damage resulting in an extensive loss of the ability to describe shape and form aspects of what she was seeing. Evidence that was convergent with Ungerleider and Mishkin emerged from the fact that Dee retained an almost undiminished ability to walk and navigate and to perform manipulative tasks such as an insertion task requiring perception of hand and object orientation. Collectively this work strongly suggests that the dorsal and ventral visual pathways have generally separable functions, with the dorsal (and largely magnocellular) pathway supporting motor action and the ventral (largely parvocellular) pathway more involved in representation tasks. The fact that the motor pathway evolved phylogenetically earlier than the ventral one and that they are evolutionarily separated adds yet a third convergent thread that these systems are distinct – without the necessity of their being utterly independent. Prima facie evolutionary evidence certainly supports that successful hunting species have compensatory mechanisms for various forms of
interception, arguing that the dorsal pathway must contain sufficient compensatory mechanisms for success. This does not, however, argue for visual or motor system compensation, only for the possibility that the ventral pathway is irrelevant (or at least not required). This opens up the possibility that phenomenal judgments made in the absence of motor function (talking about it, not doing it) could be completely irrelevant to the compensation, making the compensatory extrapolation argument moot. There have been two action-oriented FLE experiments. It was found that if the flash was self-generated, the FLE was reduced from 48ms to 37ms (López-Moliner & Linares, 2006). Similarly, Nijhawan and Kirschfeld (2003) found that a flashed signal was indeed perceived to be positioned behind the ‘felt’ position of a rod tip moved by a wrist motion, furthering Nijhawan’s belief that the FLE is related to the action compensation mechanism. This experiment substituted a manipulated rod for the rotating bar of Figure 8, moving across an arc by the wrist. Clearly, the kinesthetic spatial precision is compromised compared to the visual system.

It is the purpose of the present experiments to contribute to the resolution of these uncertainties. First, the experiments were undertaken with more observers than in most of the previous work (e.g., 15 vs. 5 for each individual experiment). This sets up possibly improved statistical power, but it also opens up the risk of having variability associated with naïve, possibly unmotivated, observers involved in a highly repetitive psychophysical experiment. Second, the experiments will utilize the same stimuli configured for six separate experiments. As described earlier the FIC and FTC can be thought of as modifications of the CM. Added to that will be the division of spatial and temporal judgments, but using the same basic stimuli. This should serve to minimize the
impact (extraneous factors/confounds) that experimental configurations might have upon result interpretations. Third, the experiments provide evidence to address some of the open questions remaining in the existing literature. These questions are cataloged following the descriptions of the FLE and some of the previous evidence and theories proposed to explain it.

**Motion Extrapolation**

When reintroducing the scientific community to the FLE, Nijhawan (1994) suggested that the phenomenon might be indicative of the neural system’s compensation for inherent neural transmission delays of between 100 and 200ms. Without such a system, he argued by example, we would not be able to pursue and catch or hit a thrown ball. The neural apparatus must, therefore, have a system whereby any object in motion is projected forward along its path in order to compensate for neural lag. The motion extrapolation process takes early motion information and projects the movement forward upon its path by, presumably, some lateral activation mechanism. Given that this extrapolative forward-projecting motion information would not be relevant for a flashed stimulus, the FLE would arise.

This mechanism introduces the issue that has thus consistently plagued FLE investigators. If the extrapolative mechanism places the moving object in real-time veridical space, and we know that the stationary object is in veridical space because it is not moving, then the phenomenon must be temporal in nature, placing the stationary object in the ‘wrong’ time. That is, the stationary object temporally lags the veridical moving object, it having been compensated for by the extrapolative mechanism. Alternatively stated, the moving object reaches a perceptual endpoint (conscious
perception) sooner due to the lateral connections that activate the cells along the projected path. The earliest possible activation, based on a single flash, could only activate cells non-directionally. By 40-70 ms, however, directionally sensitive V1 cells are activated and could hypothetically activate cells in a projected motion pathway and therefore produce directionally differentiated activation. This extrapolative mechanism leads directly to the successor theory of differential neural latency as the underlying mechanism for the extrapolative mechanism.

The initial FLE data, using CM experimental paradigms, is consistent with an extrapolative mechanism, but not differentially so by comparison with other theories. Nijhawan (1994) argues that the fact that we can veridically track a moving object (he cites a cricket bowler-batsman example) requires there to be a compensatory mechanism in place to deal with the neural latency. Inasmuch as non-moving objects do not require extrapolation to achieve veridical placement, this line of reasoning is both parsimonious and face-valid. However, it suffers from two experimental result types that seem to refute it as able to be the singular theory – the flash initiated condition (FIC) and the flash terminated condition (FTC). In the FIC, the target appears in motion coincident with the flash, while in the FTC the moving target disappears with the flash termination. If there is only extrapolation of movement happening, one would expect that objects would be seen veridically if there is no antecedent motion, but the Fröhlich effect (in which an object simply appears as if from behind a masking screen with no flash event) has essentially the same magnitude as the FLE with position mislocated in the direction of motion. More recently, Khurana and Nijhawan (1995) showed that the FIC does have an FLE of the same magnitude as the continuous motion condition (CM). Additionally, the
FTC results in near veridical placement, whereas motion extrapolation would predict that an observer would see the moving object to have passed a spatial marker when the flash occurs at the time of the crossing with simultaneous disappearance. A single experimental result that used ‘fuzzy’ moving objects (Gaussian filtered) did result in spatial ‘overshoot’ in the FTC (Fu, Shen, & Dan, 2001). This resulted in speculation that spatial uncertainty (Gaussian blurring or ‘fuzz’ is positional variance) could contribute to the overall FLE and supports extrapolation in at least some conditions.

The FIC and FTC results had appeared to refute extrapolation certainly as the sole explanation of FLE. However, Maus and Nijhawan (2008) used a clever experiment to revitalize this theory as a contender. Arguing that signal transients could suppress the otherwise tendency to position overshoot upon termination, they established an experimental geometry that suppressed these transients by extinguishing the motion signal within the blind spot. This is similar to their previous work (Maus & Nijhawan, 2006), where they faded the moving object to below threshold levels slowly to eliminate transient signals. Using the blind spot eliminated the ambiguity of the possible contribution of subthreshold signals from the fading stimulus. By comparing ipsilateral and contralateral stimuli, the results were that all observers (n=6) saw the bar disappear well into the blind spot, displaced 0.81° of visual angle, equivalent to 51 ms of temporal displacement, thus obtaining an effect with the FTC. The reverse experiment, where the stimulus emerged from the blind spot showed no difference, that is, no effect in the FIC.

Prior to this work, Chappell and Hine (2004) used the FIC to test whether a precue of the moving stimulus would change the FLE. They argued that if there is an integration window, the data available from the stationary period of the moving object
should decrease the FLE. They found that this is precisely what occurred. A pre-cue of 50ms significantly decreased the FLE (18%), and as would be expected with reasonable integration windows, longer pre-cues had little additional effect. The effect was somewhat variable across the subject pool (n=6).

These results suggest that the extrapolation account may be at least contributing to the FLE under some conditions.

**Differential Neural Latency**

Neural latency compensation is the underlying motive for the extrapolation mechanism described in the preceding section. There is no question that neural delays exist, that they exhibit systematic responses to varying conditions and have individual differences. Differential neural latency (DNL) examines the FLE from the point of view that the flashed and moving stimuli have systematically different latency properties—the moving stimulus having a shorter perceptual response time than a flashed stimulus. This could occur if, as an image traverses the retina, laterally and retinotopically connected neurons are activated by adjacent excitation. Lateral connections are certainly responsible for much of the perceptual apparatus, including the very ability to detect motion at all. This activation could be very early (Whitney, Murakami, & Cavanaugh, 2000), and virtually instantaneous if the lateral connections are within the retinal ganglia as they suggest. If the relevant lateral connections are within V1 (containing directionally selective motion detector cells), the signal would be available in about 40-70ms. The signal would become increasingly directional, albeit slower, if the relevant signal originated beyond V1. Any combination of these is also possible. In order for DNL to be explanatory for the Fröhlich effect, however, the excitation signal has to be
available virtually instantly, limiting the location of such a mechanism to the retina and certainly not beyond the lateral geniculate nucleus.

Whereas other explanations of the FLE must be supported using psychophysical data alone, a neural latency model certainly can be supported using direct measures of response times under various conditions. Macaque monkeys were shown to have a median V1 response of 85 ms to moving bars (Raiguel, Lagae, Gulyas, & Orban, 1989). This contrasts with transient response data that averaged 30 ms to 50 ms in macaques with the fastest times being 21 ms to 30 ms (Maunsell & Gibson, 1992). This portends a response advantage to a flashed stimulus rather than the reverse, at least upon initiation of both stimuli. Maunsell and Gibson also reported that lesions in the magnocellular region of the LGN slowed responses by 7-10 ms, while similar parvocellular lesions showed no such effect. This argues that the first response in V1 is along the magnocellular pathway.

Experimental results from the typical FLE CM experimental condition are consistent with a DNL explanation but not differentially so with respect to postdiction, described next. Problematic for DNL is the FIC and the Fröhlich effect, which are similar. If motion across the retina creates an ‘activated path’ in order for the moving object to reach a perceptual endpoint before the flashed object, then the FIC has little opportunity to do so. Yet the magnitude of the FLE in the FIC is at least similar to the CM. In the Fröhlich effect, there is no competitive flash event and yet observers still locate the originating point of the moving object along the trajectory of movement and not at the actual location of its first appearance. Nijhawan (2007) counters this indictment of the DNL theory by arguing that the requisite motion-activation within the retinal apparatus can be within 10 ms, and hence transparent to the magnitude of the FLE.
Krekelberg (2005) also claim that some neural activity is recorded in MT before V1, adding some credence to Nijhawan’s claim that motion activation can be very fast. DNL does require an activation mechanism very early in the visual path to remain viable, but this still belies the data available in the cortical response in the macaque, which infer up to a 60 ms advantage for the flashed stimulus. Alais and Burr (2003) argue that differential neural latency could not be singularly responsible for the FLE. In their cross-modal experiment, the auditory ‘flash’ which, by their logic, should have significantly decreased the FLE due to the shorter auditory transmission latency (relative to vision), actually resulted in an increase in the FLE beyond the unimodal visual FLE. They also found a unimodal ‘FLE’ for auditory stimuli in both a translation paradigm (sound traversing a sound stage) and in a frequency sweep paradigm. Explanations for these observations cannot possibly be found in differential activation of retinotopically adjacent elements in the path to the visual cortex. While it is certainly not necessary for this ‘beep lag’ explanation to be the same as the FLE, it does argue that the search for an explanation might be fruitful without DNL.

For DNL to be responsible for the FLE of continuous motion, given the disadvantage of moving stimuli at the outset, the system would have to ‘accelerate’ the moving object perceptually from an initial temporal lag to a lead. Additionally, it does not appear viable for the FIC, where the temporal advantage appears clearly in favor of the flash. This suggests a line of study aimed at characterizing the FLE at varying temporal offsets from the initiation of movement.
**Postdiction**

The FTC does not produce the typical FLE. In this configuration, the moving object disappears much closer to coincident with the flash and is located nearly veridically. Nevertheless, nearly is not exactly. For example, Baldo, Kihara, Namba, and Klein (2002) found that the moving stimulus did not reach the disappearance point in the FTC configuration. This strongly suggests that the extrapolative mechanism cannot be explanatory. If an extrapolation mechanism were all that were involved, there should be an ‘overshoot’ effect, which is not observed (Eagleman & Sejnowski, 2000). An example of an exception of that is an experimental result involving a Gaussian-filtered moving object (Fu et al., 2001) where the moving stimulus appears to overshoot the flash as would be the case in an extrapolative explanation. The induced blur adds uncertainty to the position, possibly contributing to this particular finding as Kanai, Sheth, and Shimojo (2004) argued. Additionally, Eagleman and Sejnowski compared the FLE in three conditions: the moving object either stopped, reversed direction, or continued at the time of the flash. They argued that if the extrapolative mechanism were operating and dominant, then the FLE would be the same for each of these. However, the stopped condition produced veridical perceived position and the reversal and continuous conditions produced equal but opposite effects (about 6° of displacement on a circular trajectory). Given the equivalence of magnitude of the continuous and reversed conditions, they further argued that there can be no contribution of a predictive/extrapolative mechanism, and that the position determination is therefore postdictive. Further, they estimated that the integration window of the postdiction was no more than 80ms by adjusting the point of reversal, post-flash. They showed that the
perceived position continued to progress in the direction of motion for about 80 ms, after which time the position remained constant at the approximate position that a continuous motion experiment would yield. They specifically proposed that the perceived position of the moving target was a weighted average of the target’s positions over the previous 80 ms. They suggested that real-time position determination is unnecessary in the context of motion perception. Instead, they suggest that positions are only calculated when called for by the temporal marker combined with the top-down instruction to compare the position of the moving object with a reference mark. Postdiction can account for the FLE in the continuous motion case, FIC, and FTC. For the FTC, the only datum is the position of disappearance; hence, it receives all the averaging weight. For the FIC, the averaging initiates when either the flash is seen or the moving object itself is seen, as in the Fröhlich effect. Whitney and Cavanaugh (2000) argued that if, as Eagleman and Sejnowski argue, the flash resets all motion signals, there should be a ‘blink’ effect that would briefly negate the motion signals. A succession of flashes should, therefore disrupt the motion percept, which they show does not happen. This argument is countered by Eagleman (Whitney & Cavanaugh, 2000), that a postdictive mechanism need not be all-or-nothing, opening up the question about the relationship and circumstances for predictive or extrapolative components to be operational.

**Motion Bias**

Eagleman and Sejnowski (2007) expanded and modified their previous postdiction model in a subtle but important way. Previously, their position, as described above, was that the temporal event marker (flash) initiated the process of spatial position determination, which ensued over the next approximately 80 ms. In this newer
interpretation, they also change their stance that the position signal of the moving object is simply unavailable until asked for, rather than being reset as in postdiction. This subtle change makes no predictive difference in their model, but avoids the neurologically implausible instantaneous reset mechanism (cache purge) found in the postdiction account. In essence, this is a positional averaging process starting at the moment of the flash. The motion bias model posits that subsequent movement biases the initial position determination. Furthermore, they suggest that this biasing is a systemic compensatory mechanism for perception of true position, rather than one that is in the neutrally lagged past.

Whereas motion bias (MB) and postdiction can explain much of the data in essentially the same way, there were a few clever configurations that distinguished them. In most FLE paradigms, the moving object generates the only motion signal and that object’s position is judged with respect to a spatial reference, generally the flashed object – making the comparison between motion biasing the position and postdiction a distinction without a difference. However, the flash drag phenomenon (Eagleman & Sejnowski, 2007) cannot be readily explained with postdiction, whereas a generalized MB model can address it. Flash drag is the phenomenon whereby the perceived position of a stationary object is biased by proximate motion. The closer the motion is to the stationary target, the higher the perceived displacement. This is perceptually related to the positional bias phenomenon found by DeValois and DeValois with moving Gabors (1991). If motion proximate to the point of position determination distorts that position determination, then the MB model can account for the flash drag effect. Eagleman and Sejnowski (2007) show that increasing the distance between the moving object and the
flashing object decreases the flash drag effect, supporting a ‘local space’ distortion owing to motion. Furthermore, they used a paradigm that has motion along two trajectories that in MB would sum to a resultant biasing vector along neither trajectory. They show that the position determination is indeed influenced by the vector sum.

**Attention**

Baldo and Klein (1995) proposed that the FLE could come about from differential latencies brought about by attentional shifts. This attention shift would ensue from the fact that attention would be diverted from the moving object to the flash as it happened, resulting in a lag before attention could be fully reinstated to the moving object in order to determine its position. Somewhat later, Baldo et al. (2002) performed a series of experiments that targeted both differential visual persistence (unsupported and not discussed further as a viable mechanism here) and motion extrapolation as mechanisms. Their results also showed no support for motion extrapolation, because in the FTC configuration the moving stimulus did not perceptually overshoot its disappearance point. In fact, it did not perceptually reach its disappearance point, falling short, they argue, because of a spatial averaging mechanism. The experiment that made a compelling case for attention being at least a component of the FLE was the invocation of a spatial cue for the flash. In this experiment, they ran three blocks of trials. In two of the blocks, the observer knew in which of two eccentric locations the flash would appear, whereas in the third it appeared randomly at one of these same two locations from trial to trial. The presence or absence of predictability modulated the attention to the correct location, as would be the case in a spatial cueing paradigm. Predictability, eccentricity, and the interaction between them were all significant, with predictability making more difference
with increasing eccentricity. Because response times are modulated by spatial cues (faster with valid cues, slower with invalid cues), this work along with a similar later work (Namba & Baldo, 2004), suggests that an increase in FLE is at least partially explained by attention processes. This establishes attention as a moderator of the FLE. The 2004 work showed that a valid spatial cue or predictable flash location significantly reduced the magnitude of the FLE from 36 ms (unpredictable flash) to 20 ms (predictable flash). This modulation effect of attention could be partially responsible for the variations in outcomes among experimental paradigms.

If attention is an FLE moderator, then there must be a temporal component in the FLE phenomenon, at least in those experimental paradigms used to establish it. A dual-task paradigm involving FLE should show the same tendency, increasing FLE for divided attention conditions with respect to single tasks. This relationship was demonstrated by Sarich, Chappell, and Burgess (2006), where the FLE was significantly larger (by 0.089°, 29.7ms) in the dual task condition. Collectively, these clearly establish attention as a factor in some FLE paradigms.

**Facial Chimera Anomaly**

Khurana, Carter, Watanabe, and Nijhawan (2006) presented subjects with a facial photograph that was split horizontally. The upper part of the face belonged to one famous person (e.g., Keanu Reaves) and the lower to another (e.g., Brad Pitt). The bottom half of the face moved horizontally across the screen while the upper half of the face was briefly flashed at some spatial offset from alignment. The task was to either identify the face (recognition task) or make an alignment judgment regarding the face halves. Even though the alignment judgment reflected the typical FLE, recognition
accuracy was better when the objects were physically aligned at the flash and therefore did not reflect the FLE (Figure 10). This indicates that position determination is subject to motion compensation in a way that meaning extraction is not. This may indicate that the FLE either relies primarily upon the dorsal stream, that the parvocellular system is not highly involved in the FLE. Placing the FLE in the more evolutionarily primitive dorsal stream simplifies modeling it to an extent.

**Foveopetal / Foveofugal anisotropy**

Shi and Nijhawan (2008) showed that there is a clear foveal approach dependence upon the FLE magnitude, and that it has two distinct components. First, the mislocalization of the moving object is greater in the foveopetal (movement toward the fovea) condition. Second, the flash drag effect was seen in the foveofugal condition (pulling the apparent flash to a more eccentric position), while in the foveopetal condition the flash was repulsed (pushing the flash to a more eccentric position). The combination of these two observations, in continuous motion paradigms, diminishes the FLE in the foveofugal condition, and enhances in the foveopetal condition.

These results are consistent with an earlier study performed in the FTC. Kanai, Sheth, and Shimojo (2004) obtained varied configuration dependent FLEs. When
specifically examining the foveal approach condition, they obtained FLEs for both levels of foveal approach, but a significantly larger one in the foveopetal condition. However, Kanai et al.’s data showed an FLE in all cases of the FTC, whereas Baldo et al.’s (2002) data reported a flash lead in the FTC.

**Neural Computational Model**

The final model to be discussed here is the one proposed by Baldo and Caticha (2005) that is based upon a highly simplified but biologically plausible neural network architecture and potentially explained a significant amount of the data in existence up to that point. This model is based upon a generalized 3-layer neural architecture (layers: input-hidden-output) that includes an array of features not specific to the task of explaining the FLE, but rather ones that have accepted neuronal properties. These include graded membrane potentials consistent with retinal bipolar cells (Barlow, 1953), temporal integration consistent with the simplest of leaky-integrate-fire (LIF) neural models (biem Graben, Liebscher, & Kurths, 2008), and antagonistic symmetrical center surround receptive fields consistent with those found in the LGN, V1, and retinal ganglion cells. Figure 11-1 shows the circuitry for the LIF model. In this spatially one-dimensional model, an input layer is supplied with a graded scalar value (presumptive luminance from a bipolar cell) that connects to five contiguous nodes in the surround.
The input layer in this description could be a retinal ganglion cell, as they receive signals from the graded bipolar cells. This same pattern connects each position of the hidden layer to the output layer below it (i.e., each node in the hidden layer is connected to five nodes from the input layer and five nodes in the output layer). The hidden layer might be thought of as the lateral geniculate nucleus and the output layer as area V1. Given that the response times at V1 in macaque monkeys can be as low as about 20ms (Maunsell & Gibson, 1992), the model’s connection pattern is not an unreasonable analog in terms of synapse count. The spatial positions of nodes are linear only in the direction of motion and of arbitrary dimension and time units. Although arbitrary, the model is constrained by the spatial reality of the receptive fields and the temporal dynamics of neuronal behavior. They are simply unspecified in the proposed model. The model uses the typical mathematical function of a leaky integrator (biem Graben, Liebscher, & Kurths, 2008, p. 199). In equation 1, \( x_i(t) \) is the activation at any time \( t \), \( \alpha_i \) is the leak rate (varies from 0-1), \( f \) is the activation function of the \( i^{th} \) unit (often logistic, but Baldo and Caticha establish it as step function of values 0 and 1), and \( y_i(t) \) is the summative weights of the nodes with inputs to the \( i^{th} \) unit. Baldo and Caticha approximate this as a numeric-stepwise integration with small ‘ticks’ of arbitrary, but small time units. The computations follow a pattern such that each position at time \( t \) adds the decayed value

\[
\frac{dx_i(t)}{dt} = -\alpha_i x_i(t) + \alpha_i f(y_i(t))
\]

of its own position plus the sum of the values of its connection points at the previous time \( t-1 \). By varying connection weights, thresholds and decay rates, the model is thus ‘tuned’ to effect plausible outcome predictions.
The claimed importance of this model approach is that it makes predictions that accommodate much of the existing literature. It also successfully separates spatial and temporal components of the FLE, specifically regarding the FIC, where this model states that the FLE magnitude is explicitly driven by a spatial mechanism, disregarding any temporal precedents. In other words, a temporal order judgment (TOJ) between the moving stimulus and a flashing stimulus would be unrelated to the spatial offset noted in the experimental literature.

I implemented the model in Excel and was able to reproduce Baldo and Caticha’s (2005) demonstration data, with an important exception. The parameters of the model precisely needed to replicate their moving vs. stationary comparison chart were not internally consistent, i.e., two slightly different connection weights and decay values were required. Extending the model to the FTC condition shows that there should be a premature extinction of the moving stimulus, which is consistent with Baldo et al. (2002), but contrary to Kanai et al. (2004), and Eagleman and Sejnowski (2000). As will become clear, most of the hypotheses tie to predictions made by this model, and an additional one specifically stems directly from the proposed extension to the FTC that was not discussed in their original paper.

Whereas Baldo and Caticha’s model is an interesting alternative to the existing theories and has the advantage of parsimony and a plausible, if too simple, anatomical analog, its implementation has a significant issue that must be addressed. In demonstrating the model’s output for the FIC case, Baldo and Caticha allow the stationary stimulus to remain ‘on’ for several time periods, while the moving stimulus moves in each time period. With digitally presented stimuli, this means that the flash is
not presented for the system’s minimum time for a given frame rate. Rather, the flashed stimulus accumulates its input signal over several frames. If one increases the input strength to a level that induces output response in a single simulated frame, the moving stimulus signal responds in kind, blunting the model’s response to the FIC. Additionally, as the stimulus moves along the model path by one neural connection step (the minimum spatial increment), there is a commensurate one-increment output offset. In reality, the magnitude of such an offset would be one neural visual receptive field wide, not the large effect (e.g., 50ms FLE at 10°/s = 30 min are FLE) one typically observes. Whereas the size of peripheral V1 receptive fields are of this magnitude, to explain any FLE near the fovea the input layer’s field width would require more ‘wiring’ unless each input point is the result of more than one neuron. The model has promise and parsimony as it is presented, but may require significant additional depth to quantitatively explain the FLE under its various configurations.

**Neural Net Model Predictions in FIC**

The following sequence of graphics shows how Baldo and Caticha (2005) demonstrated the FLE in the FIC. For the flash, the eventual percept emerges in the same column where the stimulus was presented. However, for the moving stimulus, the sequence of images in Figure 11-2 show how the percept emerges shifted in the direction of motion. In panel A, the light source is in position 3 and the middle and output layers are unexcited. In panel B, the source has shift to position 4 and the hidden layer is now active, because the input layer is a graded potential and outputs to the hidden layer regardless of excitation level. In panel C, the output layer begins to show excitation that increases in panel D and finally exceeds the threshold of the output layer (perception) by
Figure 11-2. Panels A-E show the cascade of the neural net model as the light source moves from left to right across the retinal positions. The original input is in position 3 (flashlight in Panel A), whereas the first output (Panel E) is in position 4.

Panel E. However, the position that first reaches the threshold of perceptual output is 4 not the originally excited 3. Assuming that the flash was coincident at 3, this represents the FIC FLE. It is clear from this representation that the output layer is temporally behind the input layer as would be expected in a trailing spatiotemporal averaging mechanism. Position 4 reaches a perceptual endpoint because a pair of retinotopically adjacent positions in the hidden layer remains above threshold and their outputs sums.

There are many potentially adjustable parameters in this model, but this instantiation uses symmetric connection weights that are well represented by the distribution of the hidden layer in panel B. The other parameter in this depiction is the decay rate, which is a uniform 60% across all layers. This is not necessarily required, but simplifies the representation. The input layer in panel E shows the trailing decay.
Hypotheses and Research Questions

Hypothesis 1

This hypothesis emerges from the potential separation of temporal and spatial elements of the FLE. Baldo and Caticha’s (2005) model argues for a spatially driven FIC FLE that is independent of temporal considerations. The DNL theory (e.g., Whitney et al., 2000) argues that the FLE is based on motion activating neurons ahead of the then-position of the moving stimulus creating a temporal advantage. Shi and Nijhawan (2008) argue that the anisotropy effect is temporal in nature, citing Jancke, Erlhagen, Schoner, and Dinse (2004), who claim a neurophysiological basis for differential latencies between foveofugal and foveopetal motion. Based upon these arguments, Baldo and Caticha’s proposed neural model would predict there would not be anisotropy in either the FIC or FTC spatial experiments, owing to the exclusively spatial mechanism, and no accommodation having been made for the flash drag effect. In the balance of the experiments there should be a significantly higher FLE measured for the foveopetal conditions vs. the foveofugal conditions. Confirmation of this hypothesis will be supportive of Baldo and Caticha’s neural representation of the FLE, while at the same time providing evidence against purely temporal alternative mechanisms.

Hypothesis 2

When measuring the spatial FLE, luminance of the flashed and moving stimuli will be varied. Based upon several past studies (e.g., Purushothaman, Patel, Bedell, & Öğmen (1998); Patel, Öğmen, Bedell, & Sampath (2000); Krekelberg & Lappe (2001)), the combination of low-luminance flashing stimulus and high-luminance moving stimulus (low $I_{\text{flashing}}/I_{\text{moving}}$) will produce a larger FLE in the CM paradigm than the
reverse of high-luminance flashing stimulus and low-luminance moving stimulus (high $I_{\text{flash}}/I_{\text{moving}}$). Based on Baldo and Caticha’s (2005) model, the FTC and FIC paradigms will be differentially affected according to hypotheses 3, 4, 5, and 5a.

**Hypothesis 3**

In the FTC paradigm, based upon Baldo and Caticha’s model, a sufficiently high luminance ratio (high $I_{\text{flash}}/I_{\text{motion}}$) will induce a flash lead effect, as the excitatory cascade of the moving target is insufficient to activate the last position of the moving target prior to extinction. In other words, the moving stimulus will disappear short of its actual final position. This direction of the effect is the same as in hypothesis 2, with increasing $I_{\text{flash}}/I_{\text{moving}}$ ratio decreasing the FLE. However, in this case, the specific hypothesis is that the premature extinction of the moving stimulus will produce a flash lead, not simply a reduction of flash lag, as in hypothesis 2.

**Hypothesis 4**

Hypothesis 3 predicts that the perceived extinction point of the moving stimulus will fall short of the actual disappearance point. If space and time are intimately connected, the moving stimulus should extinguish *temporally sooner* as well. Thus, in the FTC paradigm, a high luminance ratio (high $I_{\text{flash}}/I_{\text{moving}}$) will result in the flash extinguishing after the moving stimulus and a low luminance ratio (low $I_{\text{flash}}/I_{\text{moving}}$) will result in the flash extinguishing before the moving stimulus.

**Hypothesis 5**

In the FIC paradigm, the moving stimulus requires some distance downstream of the origination point to reach a perceptual endpoint. The suggested mechanism in the Baldo and Caticha (2005) neural model is independent of the temporal order and
therefore only variables that involve spatial judgments would affect this position judgment. Therefore, even a high luminance ratio (high $I_{\text{flashing}}/I_{\text{moving}}$) will be unable to overcome the spatially-induced FLE, as the excitatory cascade of the moving target requires space to reach its perceptual endpoint.

This hypothesis is a null-effect hypothesis and alone would be less interesting, but in this context is useful to establish the strength of the proposed spatially-driven FIC FLE.

**Hypothesis 5a**

In the FIC paradigm, the moving stimulus’ luminance should affect the FLE, whereas the flashed stimulus luminance should not. Specifically, a low-luminance moving stimulus (which should serve to reduce the FLE in CM conditions) should produce a higher FLE than a high-luminance moving stimulus, because according to Baldo and Caticha’s model, the position of the moving stimulus will be further downstream before the summing function reaches the perceptual threshold. This is contrary to the effect direction posited in hypothesis 2, and generally, contrary to the direction one would infer from the Hess effect. Support for hypothesis 5a indicates a support for the separation of spatial and temporal factors in the FLE, at least in the FIC case.

**Hypothesis 6**

In the FIC condition, the ratio of stimuli luminances will be tested for its effect upon the perceived temporal order of the moving and flashed stimuli. Specifically, the combination of a high-luminance flashed stimulus and a low-luminance moving stimulus (high $I_{\text{flashing}}/I_{\text{moving}}$) will produce a temporal order judgment favoring the flash compared
to the reverse (low flashed & high moving, low $I_{\text{flashing}}/I_{\text{moving}}$). The Hess effect, as described earlier, argues for this directionally because of the connection made between luminance and latency, consistent with a leaky-integrate-fire system. Baldo and Caticha (2005) specifically argue for a reversal of temporal precedence based upon stimuli luminances.

Research Question

The motion extrapolation theory has its roots in the neural/behavioral correction for the neural basis of perceptual lag. Success of the individual would be based upon the individual’s adaptation to their unique neural delays. Studies in macaques (Maunsell & Gibson, 1992; Chen et al, 2007) clearly indicate individual subject latency differences from stimulus to V1 (20ms - 31ms) and other points in both striate and extrastriate cortex (area V4, inferotemporal (IT), middle temporal plus (MT+), medial superior temporal (MST), dorsal superior temporal sulcus (STS$_d$) and intraparietal (IP) cortex). Given these differences, and assuming that individuals can all perform successful intercept behaviors, it follows that the compensation is also variable. If the compensatory mechanism is found at least partially in the visual system, this could lead to individual variability in the FLE that is related to transmission delays. While simple reaction time (RT) is a confounded surrogate for transmission delays, sufficient statistical power might reveal a positive relationship between simple RT and FLE magnitude, the evidence for which would lend veracity to the idea that the FLE is a manifestation of this compensation system.
Narrative Summary of Experimental Series and Outcomes

There were two series of experiments conducted. The first series was terminated after about 85% of the planned data collection was completed based upon a preliminary data analysis. Many of the participants to this point had staircases indicative of an unstable criterion. This observation led to a reconfiguration of the experiments. The stimulus aspect ratio was increased, seemingly making its position easier to judge. An eye tracker was added to ensure that the participants’ gaze remained fixed on a fixation point. The trailing edge of the stimulus was chosen to be used as the point of judgment as this was deemed easier to judge by the members of the lab. Finally, the key press responses were made more intuitive and compatible by eliminating the bi-directionality of motion (initially chosen to suppress motion after effect) so that the keyboard left and right arrows corresponded to observations. One of the seven experiments of the first series (speed x foveal approach) was dropped from the second series.

The second series of data were collected based upon the changes indicated. As this series also experience significant data issues, a data replacement methodology was implemented. However, given its success in Series 2, this replacement strategy was also implemented in Series 1, and ultimately both series were used to evaluate the hypotheses.

Although each hypothesis in turn was evaluated, most with partial support, an integrated view of the overall experiment will be presented in this summary. Here, we will compare the neural network model (NN), postdiction cum motion bias (MB), and differential neural latency (DNL). These propositions are amalgams of the more specific hypotheses that were tests.
Proposition 1: In FIC-T, DNL predicts that the moving stimulus would be seen first (TOJ), whereas the NN net would not because the NN is spatially driven in FIC. Outcome: The flash is seen first by a significant and important amount, providing evidence against DNL as explanatory for FIC.

Proposition 2: In FIC-S DNL’s latency-based effect would predict a brighter moving stimulus to have a larger FLE, whereas the NN predicts the opposite. Additionally, due to Hess, the MB would also predict this direction of effect. Outcome: A brighter moving stimulus has a significantly smaller FLE than dimmer, providing evidence against both DNL and MB as explanatory for NN.

Proposition 3: In the FTC-S, the temporally based DNL model does not predict a flash lead, MB predicts that the FTC-S outcome is veridical and the NN predicts a flash lead. Outcome: There was a significant flash lead in both Experimental Series, supporting the NN and providing evidence against either MB or NN being explanatory of the FTC.

These results support that either there is a mixture of mechanism across the FLE paradigm spectrum (from FIC to CM to FTC) or that the MB and DNL are special heuristic cases that explain some but not all of the FLE results, whereas an NN model may be developable into a comprehensive quantitative model for all of the FLE cases.

Experiments

General

Two series of experiments were performed. The entire first series was concluded prior to the second one beginning. Both were performed in the same laboratory setting and used the same stimulus-generating software and display hardware. The second series
essentially replicated the first with some methodological differences that will be discussed in detail within each section. The methodological changes made for the second series were undertaken to overcome task difficulties participants incurred in the first series. The initial data analysis of the first series led to the experimental reconfiguration used in the second. Ultimately, both sets of data were analyzed identically and both series’ results presented.

**Experimental Series 1**

In experiment Series one there are seven discrete experiments summarized in this section, and described more fully in the individual sections that follow.

Experiment 1 – simple reaction time to a visual stimulus

Experiment 2-Sp – FLE measured in the continuous motion paradigm (CM) varying speed (8°/s, 12°/s, 16°/s) and foveal approach (foveopetal vs. foveofugal)

Experiment 2-L – FLE measured in the continuous motion paradigm (CM) varying flash and moving stimulus luminance (high and low) and foveal approach (foveopetal vs. foveofugal)

Experiment 3-S – Spatial FLE measured in the flash-initiated condition (FIC) varying flash and moving stimulus luminance (high and low) and foveal approach (foveopetal vs. foveofugal)

Experiment 3-T – Temporal FLE (temporal order judgment – TOJ) measured in the flash-initiated condition (FIC) varying flash and moving stimulus luminance (high and low) and foveal approach (foveopetal vs. foveofugal)
Experiment 4-S – Spatial FLE measured in the flash-terminated condition (FTC) varying flash and moving stimulus luminance (high and low) and foveal approach (foveopetal vs. foveofugal)

Experiment 4-T – Temporal FLE (TOJ) measured in the flash-terminated condition (FTC) varying flash and moving stimulus luminance (high and low) and foveal approach (foveopetal vs. foveofugal)

Apparatus - General

The stimuli were generated and presented using Psykinematix software (release 1062, KyberVision, Montreal, Canada, psykinematix.com) and run on an iMac 10,1 (Intel Core 2 Duo, 3.06 GHz; NVidia GeForce 9400 256MB). The stimuli were displayed on a 23” Samsung LED monitor (Model S23A750D) with a resolution of 1920 x 1080 pixels, a 120 Hz refresh rate, and a 2ms gray-to-gray response time. From the viewing distance of 57 cm, the screen subtended 51.0 deg x 28.5 deg. Observer responses were made using a standard keyboard.

Procedure - General

Each participant was introduced to the experiment and asked to read and sign the Consent to Participate form. Participants were seated behind a non-occlusive black drape that was designed to eliminate stray reflections from the room onto the screen. The room itself was illuminated by a 40-watt diffused light source situated 6 feet from the participant on the opposite side of the drape. The only window in the room was covered with an opaque occluder, the door was closed, and the lights turned off. A Minolta Chroma Meter CS-100 measured the relevant light levels. The ambient light in the room in the area of the participant was 0.4 cd/m² (white surface @ 57cm). The unlit computer
monitor had a luminance of 0.01 cd/m². The participants first undertook the reaction time study followed by the continuous motion paradigm. The participants then proceeded to one of three experiments. These were either a second single continuous motion (CM) paradigm, two flash-initiated (FIC) paradigms, or two flash-terminated (FTC) paradigms. In each case, the reaction time study was initiated only with verbal instructions followed by an on-screen refresher. In the balance of the paradigms, the participants performed a demonstration / familiarization trial with exaggerated effects to ensure clarity of instruction and the ability to perform the task. Some participants were unable to understand and follow the instructions or perform the tasks at some point in the process. In these cases, the participant was excused and none of the data used in subsequent analysis, irrespective of when their participation in the experiment was terminated.

Experiment 1 – Reaction Time

Participants

Forty-six participants were recruited (17 males: M=26.1, SD=9.8; 29 females: M=23.2, SD=4.8). All were naïve to the experimental hypotheses. The participants were recruited from the Wright State University psychology department. The majority were undergraduates taking an experimental methods class with Mr. Gabbard or a perception class with Dr. Watamaniuk. These participants were offered extra credit for the class they were taking.

Apparatus

Participants required just the spacebar on a standard Mac keyboard for responses. Participants were seated in a straight-backed chair positioned to create a 57 cm viewing
distance. The computer monitor was positioned on a desk so that a perpendicular normal line from the middle of the monitor would intersect the approximate bridge of the nose.

**Procedure**

After being seated and positioned at the correct viewing distance from the monitor, the participants received instructions that they were to react as quickly as possible to the presentation of a stimulus on the screen. The stimulus was an amorphous array of numerous rectangles each of about 1° x 0.2° visual angle presented at a luminance of 152 cd/m² on a black (0.35 cd/m²) background. The entire array spanned about 8° of visual angle. The stimulus was flashed for 250ms. The participant pressed the space bar in response to the stimulus. The next stimulus was presented at a random time between 2 and 4 seconds subsequent to the bar press in order to avoid anticipation of the next presentation. This process continued for approximately 30 cycles before manually terminated by the participant at the instruction of the experimenter, who was counting them.

**Experiment 2-L: Continuous motion FLE 1 – (CM1)**

**Participants**

All 46 observers from Experiment 1 participated in this experiment. However, four observers were excused because they were unable to perform the task.

**Apparatus**

The apparatus was as described in the general apparatus section and in Experiment 1.
Procedure

Participants were given approximately a 3-minute rest after completing Experiment 1 while the experimental software was readied. Participants remained seated behind the black curtain. The experimenter described the experiment aloud, discussing the nature and relationship of the moving and flashing stimuli as well as the criticality of maintaining gaze on the central fixation target during the stimulus presentation. This was repeated, as required until the participant clearly understood their task by explaining it back to the experimenter. The participant was then taken through a practice run of the experimental protocol (exaggerated spacing between the flashed and moving stimuli; no data collection) until the participant appeared to grasp the task sufficiently well to make a series of consecutive correct responses.

This experiment had a 2 x 3 factorial design with foveal approach (foveofugal and foveopetal) and moving stimulus speed (8°/s, 12°/s, & 16°/s) as variables. The two stimuli (one moving and one fixed) presented in each trial were 3.5° tall x 0.07° wide. The moving stimulus originated randomly in one of four starting positions, two on the left side, one 1.85 deg above and one 1.85 deg below the center of the screen (at the midline of the stimulus), and two analogous locations on the right side of the screen. It then moved horizontally to the opposite side of the screen at one of the three speeds indicated above. At some point along the moving stimulus’ trajectory, the flashed stimulus appeared for a single frame (8.33 ms). The participant’s task was to indicate whether the moving stimulus had proceeded beyond the horizontal position of the flashed stimulus at the time it was flashed. An up arrow on the keyboard indicated passed (P) and a down arrow indicated not passed (NP). A left or right arrow indicated that the
participant either had missed the flash, or otherwise was unsure (DK). The six conditions (3 speeds crossed with foveopetal/foveofugal motion) were presented as randomly interleaved staircases. In each trial, the time at which the flashed stimulus appeared, relative to the arrival of the moving stimulus at the same horizontal position, was determined based upon the observer’s previous response. In trial one, the time of the appearance of the flash was 150 ms before the moving stimulus reached the flashed stimulus’ position, making it an easy judgment for the observer. If the observer judged the moving stimulus as ‘not passed,’ the difference in time between when the flash occurred and when the moving stimulus reached its horizontal position (delay) was decreased by 80 ms. This process continued for every trial until the observer changed their response from ‘not passed’ to ‘passed’ (called a reversal), and then the difference in time between the flash and moving stimulus arrival time was increased by 50 ms. At the next reversal, the delay was decreased by 50 ms. For the next and subsequent reversals, the delay was altered by 16.67 ms (2 frames). Each of these one-up one-down staircases continued until the observers changed their response 10 times (e.g., 10 reversals). This one-up one-down staircase procedure is designed to bring the observers to a level of the manipulated variable where their responses oscillate, called the point of subjective equality (PSE) or 50% point of discrimination (Wetherill & Levitt, 1965). The experimental software reported the mean and standard deviation of the delay values for the last six reversals as an estimate of the PSE (the point at which the observer perceived the moving stimulus to arrive at the horizontal location of the flash at the time of the flash) for that observer. It took approximately 15-20 minutes for an observer to complete all 6 interleaved staircases. A PSE of zero time difference (or delay) would indicate that
the observer perceived the position of the moving stimulus to be aligned with the horizontal position of the flashed stimulus at the moment of the flash. Positive delay values indicate that the flash occurred after the moving stimulus had passed the actual horizontal position of the flashed stimulus, whereas negative values indicate that the flash occurred before the moving stimulus had reached the actual horizontal position of the flashed stimulus.

**Experiment 2-L: Continuous motion FLE 2 (CM2)**

**Participants**

Fourteen randomly selected observers from Experiment 1 participated in this experiment.

**Procedure**

Participants were given approximately a 3-minute rest after completing Experiment 2-S while the experimental software was readied. The experiment proceeded in a similar fashion as Experiment 2-S, with a task description followed by a demonstration of the experiment. In this case, because the participant had just completed so similar an experiment, the orientation went more quickly.

This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (56 cd/m² and 242 cd/m²), and flashing stimulus luminance (56 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The eight conditions were presented as random interleaved one-up one-down staircases. All other aspects of the experiment were as in Experiment 2-S, except that it took about 33% longer to complete because of the increased number of conditions (eight vs. six). In this experiment, every staircase began with an initial delay
of -125ms (the flash appeared before the moving stimulus reached the flashed stimulus’ position – referred to as early flash) and the delay was decreased by 33.33 ms (4 frames) after every ‘correct’ response until the first reversal. The delay was then adjusted by 16.66 ms after every trial until 2 more reversals occurred, after which the delay was adjusted by 8.33 ms after every trial until the remaining reversals had occurred.

**Experiment 3-S: Flash-initiated FLE – spatial (FIC-S)**

**Participants**

Fifteen randomly selected observers from Experiment 1 participated in this experiment. None of these observers participated in Experiment 2-L or Experiments 4-S and 4-T.

**Procedure**

Participants were given approximately a 3-minute rest after completing Experiment 2-S while the experimental software was readied. The experiment proceeded in a similar fashion as Experiment 2-S, with a task description followed by a demonstration of the experiment. As this experiment was somewhat different from Experiment 2-S, in that both relevant stimuli were presented at the beginning, the demonstration phase was sometimes several minutes, however the endpoint of the demonstration phase was again a series of correct decisions made on obvious judgments.

This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (56 cd/m² and 242 cd/m²), and flashing stimulus luminance (56 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The variable being adjusted within the trials was the position of the flashing stimulus and this was done precisely as in Experiment 2-S. Zero adjustment
meant that the flashing stimulus and moving stimulus were aligned (i.e., the flashing stimulus was aligned with the point of origin of the moving stimulus. Each trial presented the stimuli initiating near the fixation point. In the foveopetal condition the stimuli were presented 0.75cm opposite the direction of motion from the center point (i.e., 0.75cm left of center for rightward motion). In the foveofugal condition, the stimuli were presented 0.75cm in the same direction as the direction of motion. In each trial, the position of the fixation point was randomly adjusted within 0.25cm of the actual center point in an effort to reduce further the ability of the participant to anticipate or use artificial position cues. The eight conditions were presented as random interleaved staircases. The offset variable was initially set to a mean of zero with a -0.3° to +0.3° degree randomizing range. The adjustment increment was constant at 0.05°.

**Experiment 3-T: Flash-initiated FLE-temporal (FIC-T)**

**Participants**

All participants from Experiment 3-S performed Experiment 3-T, however three observers were excused because they were unable to perform the task.

**Procedure**

Participants in this experiment were given approximately a 3-minute rest from Experiment 3-S that had been concluded immediately prior while the experimenter set up this experiment in the software. The experiment was operated as in Experiment 3-S.

This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (56 cd/m² and 242 cd/m²), and flashing stimulus luminance (56 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The variable being adjusted within the trials was the timing
delay of the flashing stimulus. The adjustment increment was a constant 20 ms delay, with an initial delay value randomized between -100 ms and +300 ms. The fixation point and foveofugal vs. foveopetal conditions were managed as in Experiment 3-S. Zero adjustment meant that the flashing stimulus and moving were initiated simultaneously (i.e., the flashing stimulus was presented on the same 8.33 ms video frame as the initial frame of the moving stimulus). The eight conditions were presented as random interleaved staircases. All other aspects of the experiment were as in Experiment 3-S.

**Experiment 4-S: Flash-terminated FLE-spatial (FTC-S)**

**Participants**

Thirteen of the participants randomly selected from Experiment 1, but not used in Experiment 2-L or Experiments 3-S and 3-T, were used for this experiment.

**Procedure**

Participants in this experiment were given approximately a 3-minute rest from Experiment 2-S that had been concluded immediately prior while the experimenter set up this experiment in the software. The experiment was conducted as in Experiment 2-S.

This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (56 cd/m² and 242 cd/m²), and flashing stimulus luminance (56 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². In this experiment, the stimuli were initiated exactly as in Experiments 2-S and 2-L, but unlike them, the moving stimulus disappeared simultaneously with the flash. The variable being adjusted within the trials was the position of the flashing stimulus (offset). Zero adjustment meant that the flashing
stimulus and moving stimulus were aligned (i.e., the flashing stimulus is aligned with the point of disappearance of the moving stimulus). Each trial presented the stimuli disappearing near the fixation point. In the foveopetal condition the stimuli were terminated 0.75cm prior to reaching the center point (i.e., 0.75cm left of center for rightward motion). In the foveofugal condition, the stimuli were terminated 0.75cm beyond the center point of the screen. In each trial, the position of the fixation point was randomly adjusted within 0.25cm of the center point in an effort to reduce further the ability of the participant to anticipate or use artificial position cues. The eight conditions were presented as random interleaved staircases. The initial value of offset was randomized between -0.3° visual angle and +0.1°. The adjustment increment was a constant 0.05°. All other aspects of the experiment were as in Experiment 2-S.

**Experiment 4-T: Flash-terminated FLE-temporal (FTC-T)**

**Participants**

All 13 participants from Experiment 3-S were used for this experiment.

**Procedure**

Participants in this experiment were given approximately a 3-minute rest from Experiment 4-S that had been concluded immediately prior while the experimenter set up this experiment in the software. The experiment was conducted as in Experiment 4-S.

This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (56 cd/m² and 242 cd/m²), and flashing stimulus luminance (56 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The variable being adjusted within the trials was the timing of the flashing stimulus. The adjustment increment was a constant 0.00833 sec (one video
frame). The starting delay was randomized in a range described by -0.0833±0.0083sec. The fixation point and foveofugal vs. foveopetal conditions were managed as in Experiment 4-S. Zero adjustment meant that the flashing stimulus and moving were terminated simultaneously (i.e., the flashing stimulus was presented on the final 8.33 ms video frame as the moving stimulus. The eight conditions were presented as random interleaved staircases. All other aspects of the experiment were as in Experiment 4-T.

**Preliminary Data Analysis Series 1**

The data generated in Experiment Series 1 were examined prior to final analysis. This section describes that process and the deficiencies in the data that were discovered leading to Experiment Series 2. The results section describes the outcomes from the ultimate analysis process, but that was not undertaken until data from the second series were gathered.

There were no issues with the reaction time data from Experiment 1. The issues that emerged for Experiments 2-S through 4-T were common, so they will be discussed as a single general case.

In Experiments 2-S – 4-T, each participant provided a single measure for each condition. Each datum was the mean of the last six reversals of the staircase. The expectation for the last 6 of 10 total reversals is that the PSE would be bracketed by the reversals (Figure 12a). This presumes that the observer’s criterion is stable and that there are few, and ideally, no button press errors. A preliminary scan of the data suggested that these ideals were frequently not realized. I will discuss the possible sources of data errors in the discussion section. In this section, however, I will discuss the form of the data.
Non-ideal data came in two forms. First, there were noisy data resulting in a high standard deviation computed over the six reversals (Figure 12b). Second, there were cases where rather than the reversals bracketing a constant threshold value (thus forming a zero-slope function), the reversals appeared to fall along a sloping line (Figure 12c). Significance tests of the slopes of the functions defined by the final six reversals were performed. Greater than 60% of the participants had at least one datum within one experiment whose component reversals either had a significant slope ($p < .05$) or had problematic variability (there is no standard for excess variability in reversal dispersion). Because these experiments had a repeated measures design, eliminating some observers’ individual condition results would be problematic—requiring either data replacement strategies or participant exclusion. This situation motivated redesigning the experimental protocols to minimize the likelihood of problematic data.

It is worth noting at this point that there was anecdotal evidence from post-run interviews that participants had difficulty maintaining their gaze. The impact of this would be two-fold. Intermittent moving stimulus pursuit behavior would create significant FLE measurement ‘noise’ manifesting as criterion shifting between trials. Consistent moving stimulus pursuit would result in the negation of the FLE for the CM and erratic measures in FIC and FTC due to saccadic movements to maintain the target during movement transients.

**Transition from Experimental Series One to Series Two**

The data were examined in Series One when approximately 85% of the data had been collected. It became immediately apparent, after looking at individual staircases, that most participants had at least one bad datum. In a repeated-measures design, even
one bad datum prevents the data set from being used. The total number of participants needed, based upon the data collection strategy, was 45. With only about 1/3 completely viable, this meant that we would need 135 participants in total. Therefore, the decision was made to collect the data again, and change the experiment to make the judgment easier and improve the success rate. Ultimately, the new stimuli did somewhat better, but not well enough to avoid the need to replace some of the data, and with that method in place, the Series 1 data became viable again.

There appeared, anecdotally, to be three possible sources of error that were manageable. An unstable judgment criterion borne of stimulus itself, key press errors, and eye movements (pursuit) were the most likely culprits, and a change in each was implemented. To address the criterion problem, the stimulus was changed. In Series 1, it was essentially a line (3.5° x 0.07°; aspect ratio of 50). Examining the stimuli in the literature, a circle, or rectangle was more typically used. Therefore, the Series 2 stimuli were changed to 3.5° x 0.7°, with an aspect ratio of 5. Additionally, this enabled a choice as to whether the leading or trailing edge of what was now a discernible rectangle should be the point of judgment. A poll taken among the laboratory personnel as to judgment ease resulted in the trailing edge being selected. The larger stimulus appeared brighter, resulting in the need for the low-luminance condition to be made dimmer. The gap between the stimuli was made as small as practicable, allowing just enough room for the fixation point not to overlap the stimuli as they passed.

The second strategic change was the elimination of the direction balancing of the presentation. The counterbalance was to suppress possible MAE incursions. In Series 1, the moving stimulus was presented as originating from any of four positions, the outside
edge of the four screen quadrants. This resulted in judgments not being easily mapped to keyboard responses as ‘judged after’ would be left or right depending upon the direction of motion. In Series 1, ‘up arrow’ was ‘after’. This is somewhat less intuitive than left and right being mapped to the left and right arrow for response. To create that mapping possibility, Series 2 had only left to right movement, but maintained upper and lower hemifield presentations to still mitigate the MAE potential.

The last change between the two series was the addition of an eye tracker. Eye movement data were not recorded, but each participant was monitored with the eye tracker to determine whether they could maintain their gaze while judging the presentation. During each instruction period, the participants would complete a number of trials while the experimenter monitored their eye movements with the eye tracker. The amplification factor on the eye-tracker output screen made it completely clear when the participant pursued the moving target. Sporadic monitoring during the data collection itself further ensured compliance.

<table>
<thead>
<tr>
<th>Table 0</th>
<th>Summary of differences between Series 1 and 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Series 1</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>50</td>
</tr>
<tr>
<td>Origin Points for Moving Stimuli</td>
<td>4 (upper left, upper right, lower left, lower right)</td>
</tr>
<tr>
<td>Luminance levels (cd/m²)</td>
<td>242 (high), 56 (low)</td>
</tr>
<tr>
<td>Number of Experiments</td>
<td>7</td>
</tr>
<tr>
<td>EyeLink eye tracker</td>
<td>No</td>
</tr>
<tr>
<td>Judgment point</td>
<td>Single line</td>
</tr>
</tbody>
</table>
Experimental Series Two Description

In experiment series two there are five discrete experiments summarized in this section, and described more fully in the individual sections that follow:

- **Experiment 1** – Reaction time measured precisely as in Series 1, Experiment 1;

- **Experiment 2-L** – FLE measured in the continuous motion (CM) paradigm varying flash and moving stimulus brightness and foveal approach (2×2×2 repeated measures);

- **Experiment 3-S** – Spatial FLE measured in the flash-initiated condition (FIC) varying flash and moving stimulus brightness and foveal approach (2×2×2 repeated measures);

- **Experiment 3-T** – Temporal FLE measured in the flash-initiated condition (FIC) varying flash and moving stimulus brightness and foveal approach (2×2×2 repeated measures);

- **Experiment 4-S** – Spatial FLE measured in the flash-terminated condition (FTC) varying flash and moving stimulus brightness and foveal approach (2×2×2 repeated measures);

- **Experiment 4-T** – Temporal FLE measured in the flash-terminated condition (FTC) varying flash and moving stimulus brightness and foveal approach (2×2×2 repeated measures).

**NOTE:** Experiment 2-Sp of Series 1 was not repeated in Series 2. The preliminary analysis showed no speed dependence, which was consistent with the literature.
General Apparatus

The second series of experiments used the same software as in the first along with the same display monitor. However, in this second series a critical new piece of apparatus was added. The post-experiment interviews from the first series indicated that some participants had a difficult time maintaining their gaze on the fixation point during the trials. Inasmuch as this phenomenon depends on a fixed gaze, it was essential for the second series to ensure, to the extent practicable, that participants maintained fixation.

The stimuli were generated using Psykinematix (release 1064) running on a Mac Pro (Mid 2010, 2 x 4 2.4GHz Quad-core Intel Xeon; ATI Radeon HD5770 1024 MB graphics adapter). The display was the same Samsung S23A750D as in Experiment Series 1. Eye movements were monitored using an EyeLink 1000 video-based eye tracker (SR Research) with a sampling rate of 500 Hz, using the desktop mount for head-free tracking, and responses were made using a standard keyboard.

Procedure for Experiment Series 2

Prior to running any of the specific experiments, each participant was prepared for the eye tracker by placing an infrared ‘bulls eye’ target about 1” above the bridge of his or her nose. The eye tracker monitored both the ‘bull’s-eye’ target and the observer’s right eye (each at 500 Hz) which enabled the eye tracker to compute eye position even in the event of a head movement. The eye tracker displayed the participant’s gaze pattern on a separate monitor positioned to be discretely observed by the investigator. For each experimental protocol, there was a specific training procedure. During the first one of these, participants were monitored on a number of trials to ensure that they could maintain their gaze. Additionally, they were monitored at irregular intervals to ensure
that the training-trial observation of gaze fixation was maintained throughout the experiment.

**Procedure - General**

Each participant was introduced to the experiment and asked to read and sign the consent to participate form if he or she had not participated in the First Experimental Series. Participants were seated behind a non-occlusive black drape that was designed to eliminate stray reflections from the room onto the screen. The room itself was illuminated by a single light source situated 6 feet from the participant. The room’s window was blocked with cardboard, the door was closed, and the lights turned off. A Minolta Chroma Meter CS100 measured the ambient light in the room in the area of the participant at 0.4 cd/m². The unlit computer monitor had a luminance of 0.01 cd/m². The participants first were calibrated on the Eye-link 1000 to monitor eye movements. With the exception of Dr. Watamaniuk, Mr. Gabbard, and two lab assistants who ran multiple experiments, the naïve participants ran either a combination of Experiments 1 and 2-L, a combination of Experiments 3-S and 3-T, or a combination of Experiments 4-S and 4-T. Experiments 2-6 were 2×2×2 within-subjects factorial designs. Participants performed a demonstration / familiarization trial with exaggerated effects to ensure clarity of instruction and the ability to perform the task. Those participants who were unable to understand and follow the instructions or perform the tasks at any point in the process were excused and none of their data used in subsequent analysis, irrespective of when the sequence was terminated.

In Experiments 2-L through 4-T, the stimuli presented to the participants change aspect ratios from 50:1 as in Series 1 to 5:1 (Series 1 = 3.5º × 0.07º; Series 2 = 3.5º ×
0.7°). Participants were instructed, explicitly and with repetition, to make their judgments based upon the trailing edges of the stimuli. The increased width of the stimuli made this possible, whereas in Series 1, the stimuli were practically lines with no discernible width. The trailing vs. leading edge judgment decision was made based upon an informal survey of judgment ease taken in the laboratory.

Experiment 1 – Reaction Time

Participants

Fifteen participants were recruited (9 males: M=37.2, SD=9.2; 6 females: M=30.5, SD=15.7). Eleven were naïve to the experimental hypotheses. All but one participant were recruited from the Wright State University psychology department, the exception being a friend of Mr. Gabbard. The six undergraduate participants received extra course credit, the balance received no compensation of any kind.

Apparatus

Participants required just the spacebar on a standard Mac keyboard for responses. Participants were seated in a straight-backed chair positioned to create a 57 cm viewing distance. The computer monitor was positioned on a desk so that a perpendicular normal line from the middle of the monitor would intersect the approximate bridge of the nose.

Procedure

This experiment was conducted precisely as in Series 1 Experiment 1.

Experiment 2-L: Continuous Motion FLE 1 (CM1)

Participants

All 15 observers from Experiment 1 participated in this experiment. A 16th observer also ran the experiment, but the data were unusable (extreme outlier).
Procedure

Participants were given approximately a 3-minute rest after completing Experiment 1 while the experimental software was readied. The experiment proceeded in a similar fashion as Series 1 Experiment 2-L, with a task description followed by a demonstration of the experiment.

This experiment had a $2\times2\times2$ factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance ($48 \text{ cd/m}^2$ and $242 \text{ cd/m}^2$), and flashing stimulus luminance ($48 \text{ cd/m}^2$ and $242 \text{ cd/m}^2$) as variables. These were against a background of $40 \text{ cd/m}^2$. The eight conditions were presented as random interleaved one-up one-down staircases. The experiment took about 25 minutes to complete. In this experiment, every staircase began with an initial delay of between 95 and 105 ms (randomized) and the delay was decreased by 50 ms (6 frames) after every ‘correct’ response until the first reversal. The delay was then adjusted by 25 ms after every trial until another reversal occurred after which the delay was adjusted by 8.33 ms after every trial until the remaining reversals had occurred.

Experiment 3-S: Flash-Initiated FLE – Spatial (FIC-S)

Participants

Eighteen observers participated both in this experiment and in Experiment 3-T. Three of these participants (the experimenter, advisor, and an undergraduate lab assistant) also participated in other experiments, whereas the other 15 did not. The naïve observers comprised graduate students and undergraduates who received extra credit while taking the experimenter’s research methods class. There were 10 males (M=33.0, SD = 11.9)
and eight females (M = 23.7, SD = 7.2). One of the males’ data was unusable (outlier) and was eliminated post hoc.

**Procedure**

Participants began this experiment as soon as the eye calibration exercise was complete. The experiment proceeded in a similar fashion as Experiment 2-L, with a task description followed by a demonstration of the experiment. As this experiment was somewhat different than Experiment 2-L, in that both relevant stimuli were presented at the beginning, the demonstration phase was sometimes several minutes.

This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (48 cd/m² and 242 cd/m²), and flashing stimulus luminance (48 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The variable being adjusted within the trials was the position of the flashing stimulus. Zero adjustment meant that the flashing stimulus and moving stimulus are aligned (i.e., the flashing stimulus is aligned with the point of origin of the moving stimulus). Each trial presented the stimuli initiating near the fixation point. In the foveopetal condition the stimuli were presented 0.61 cm opposite the direction of motion from the center point (i.e., 0.61 cm left of center for rightward motion). In the foveofugal condition, the stimuli were presented 0.89 cm in the same direction as the direction of motion. The reason for this apparent asymmetry is that the trailing edge of the stimulus was 14mm left of center, and the intent was to place the left edge at 0.75cm on either side of center. In each trial, the position of the fixation point was randomly adjusted within 0.25cm of the fixation point in an effort to further reduce the ability of the participant to anticipate or use artificial position cues. The eight conditions were
presented as random interleaved staircases. The offset variable was initially set to a mean of 1° ±0.05°. The adjustment increments (implemented as above) were .4° until reversal one, .2° until reversal two, and 0.05° thereafter (0.4\0.2\0.05).

**Experiment 3-T: Flash-Initiated FLE-Temporal (FIC-T)**

**Participants**

All participants from Experiment 3-S performed Experiment 3-T. Unlike Experiment 3-S, all data were usable.

**Procedure**

Participants in this experiment were given approximately a 3-minute rest from Experiment 3-S that had been concluded immediately prior, while the experimenter set up this experiment in the software. The experiment was operated as in Experiment 3-S. This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (48 cd/m² and 242 cd/m²), and flashing stimulus luminance (48 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The variable being adjusted within the trials was the timing delay of the flashing stimulus. The adjustment increment followed a .05\0.025\0.008333 pattern with an initial delay value randomized between 75 ms and 125 ms. The fixation point and foveofugal vs. foveopetal conditions were managed as in Experiment 3-S. Zero adjustment meant that the flashing stimulus and moving were initiated simultaneously (i.e., the flashing stimulus was presented on the same 8.33 ms video frame as the initial frame of the moving stimulus). The eight conditions were presented as random interleaved staircases. All other aspects of the experiment were as in Experiment 3-S.
Experiment 4-S: Flash-Terminated FLE-Spatial (FTC-S)

Participants

Seventeen observers participated both in this experiment and in Experiment 4-T. Three of these participants (the experimenter, advisor, and an undergraduate lab assistant) also participated in other experiments, whereas the other fourteen did not. The naïve observers comprised graduate students and undergraduates who received extra credit while taking the experimenter’s research methods class. There were nine males (M=36.8, SD = 15.9) and eight females (M = 25.8, SD = 3.3). One of the females’ data was unusable (outlier) and was eliminated post hoc.

Procedure

The experiment was operated as in Experiment 3-S. This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (48 cd/m² and 242 cd/m²), and flashing stimulus luminance (48 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². In this experiment, the stimuli initiate exactly as in Experiments 2-L and 3-S, but unlike them, the moving stimulus disappears simultaneously with the flash. The variable being adjusted within the trials was the position of the flashing stimulus (offset). Zero adjustment meant that the flashing stimulus and moving stimulus were aligned (i.e., the flashing stimulus is aligned with the point of disappearance of the moving stimulus). Each trial presented the stimuli disappearing near the fixation point. The foveal approach and fixation point management was as in Experiment 3 as was the condition presentation. The initial value of offset was randomized between +0.15° visual angle and +0.25°. The adjustment increments (implemented as above) were 0.4° until reversal one, 0.2° until
reversal two and 0.05° thereafter (0.4\/0.2\/0.05). All other aspects of the experiment were as in Experiment 3-S.

**Experiment 4-T: Flash-Terminated FLE-Temporal (FTC-T)**

**Participants**

All 17 participants from Experiment 4-S were used for this experiment. One of the females’ data was removed post-hoc.

**Procedure**

Participants in this experiment were given approximately a 3-minute rest from Experiment 4-S that had been concluded immediately prior, while the experimenter set up this experiment in the software. The experiment was operated as in Experiment 4-S. This experiment had a 2×2×2 factorial design with foveal approach (foveofugal and foveopetal), moving stimulus luminance (48 cd/m² and 242 cd/m²), and flashing stimulus luminance (48 cd/m² and 242 cd/m²) as variables. These were against a background of 40 cd/m². The variable being adjusted within the trials was the timing of the flashing stimulus. The initial value of delay was randomized between +0.50 ms and 150 ms. The adjustment increments (implemented as above) were 50 ms until reversal one, 25 ms until reversal two and 8.33 ms thereafter (0.05\/0.025\/0.00833). All other aspects of the experiment were as in Experiment 3-T. The fixation point and foveofugal vs. foveopetal conditions as well as the presentation of conditions were as in Experiment 4-S. Zero adjustment meant that the flashing stimulus and moving were terminated simultaneously (i.e., the flashing stimulus was presented on the final 8.33 ms video frame as the moving stimulus. All other aspects of the experiment were as in Experiment 4-S.
Data Analysis

This section describes the process of data extraction from the experimental output, and the subsequent analysis. The reaction time data required no pre-analytical manipulation.

Each condition for each observer produced a staircase output, the last six points of which were used by the software to output two values for the dependent variable, mean, and standard deviation. Because of the nature of a staircase, there was always a minimum standard deviation, determined by the size of the adjustment increment. The three panels in Figure 12 show stylized outputs at the limits of ‘perfect’ and the two types of rejected outputs. Because of the possible severe loss of data sets if participant data were to be eliminated due to either outlier data or suspect data due to the nature of the staircases, the decision was made to replace suspect data. Replacement data were supplied for conditions according to the following method:

**Step 1:** If, for a single experiment, a participant had more than one raw datum that was >3 SD from the aggregate conditional mean over all observers (8 for a 2×2×2), that participant’s data were completely removed from that experiment.

**Step 2:** When a participant had only one errant raw datum, it was replaced by a conditional mean and a biased conditional mean for further analysis. The
conditional mean was the mean of the other participants in that experiment. The biased conditional mean was calculated as the z-score modified conditional mean. The z-score used was the mean z-score of the participant’s successful raw scores. For example, if out of eight scores, seven were successful, the z-score for each of those (using the conditional mean and standard deviation) was calculated. That z-score was applied to the conditional mean for the datum to be replaced and used in lieu of the ‘defective’ raw score. Less than 10% of the overall data was replaced.

**Step 3.** Step 2 resulted in three complete sets of data for analysis, original raw, mean-replaced, and z-modified mean-replaced. All of the ANOVAs were performed on all three data sets to examine results for the possibility that these replacements had an important impact on the outcome. Whereas there was clearly some movement of F values, and some cases where the raw and adjusted F values fell just on either side of the criterion, broadly there were no important differences. Exceptions are noted in the results sections, where only the z-modified results are reported.

**Results Experiment Series 1**

An α of .01 was used for all tests, except where noted otherwise.

**Experiment 1 – Reaction Time**

Forty-five participants performed the RT experiment. Three participants were eliminated from the entire experimental series due to an inability to perform the FLE experiments. One additional participant completed the series but the RT was slow by >3 SD and therefore that datum is not included in the RT analysis. Of the 41 remaining,
three additional participants were eliminated from Experiment 2-Sp, leaving 38 observers who completed both. These 38 data pairs were correlated (RT vs. FLE) and are presented here. Each participant had between 29 and 37 RT trials. Trials that resulted in RTs that were physiologically impossible (under 150ms) were eliminated. The fastest five RTs for each observer were averaged together to obtain the RT to be used in the correlation for that observer. Males (M=210ms, SD = 12ms) were found to be slightly faster ($t(39) = 2.94, p<.01$) than females (M=224ms, SD =18ms). Overall RT (M=219ms, SD=18ms) results were reasonably consistent with those expected of a simple reaction time to a visual stimulus (Figure 13). Correlation results will be discussed in the next section.

**Experiment 2-Sp Continuous Motion FLE 1 – (CM1)**

FLE data were collected from 42 of the original 45 participants. These data were subjected to the treatment described in detail in the data analysis section and resulted in 39 FLE observations for each of the six conditions. After determining that the data passed both Bartlett’s (test statistic = 6.63, $p = .25$) and Levene’s (test statistic = 1.01, $p = .411$) tests
for homogeneity of variance, a 2-way repeated measures ANOVA (speed x foveal approach) was performed. The results were that speed was not significant \( F(2,76) = 2.52, p = .087 \), whereas foveal approach (Figure 14) was significant \( F(1,38) = 11.6, p = .002 \). There was no significant interaction between speed and foveal approach \( F(2,76) = 0.65, p = .52 \). Collapsing the observations across speed into the two foveal approach conditions, the FLE measured for the foveopetal condition was 40.0 ms (SE = 8.1 ms), resulting in a significant value relative to the null of no FLE \( t(38) = 4.93, p < .01 \). In contrast, the foveofugal condition showed no significant FLE \( (M = 2.7 \text{ ms}, SE = 10.6 \text{ ms}). \)

These results suggest that the correlational analysis of RT with FLE should be separated into the two foveal approach conditions. Of the 42 participants in this experiment, only 41 had reliable RT data and 3 other participants had their data eliminated for reasons delineated in the preliminary data analysis series 1 section, leaving 38 RT-FLE pairs for correlation. Neither correlation result was significant (foveopetal condition, \( r(36) = -.22, p > .05 \); foveofugal condition, \( r(36) = -.26, p > .05 \)). The threshold of significance for 36 df = ±0.321.

**Experiment 2-L – Continuous-Motion FLE 2 (CM2)**

This experiment was similar to Experiment 2 but varied luminance for both moving and flashing stimuli. Fourteen observers from the previous experiment participated. After determining that the data passed both Bartlett’s (test statistic = 4.14, \( p = .76 \)) and Levene’s (test statistic = 0.63, \( p = .727 \)) tests for homogeneity of variance, a 2×2×2 repeated measures ANOVA (flash luminance, moving luminance, foveal approach) produced no significant effects \( (\alpha = .01) \), although the effect of luminance
level of the flashing stimulus neared significance ($F(1,13) = 5.92, p=.03$). Noteworthy is that foveal approach was not significant, even though this was essentially the same as Experiment 2-L where it had a significant effect. Averaging all participants’ FLE values collapsed across all conditions produced an FLE of 54.1 ms and resulted in a one sample $t$-test that was significant ($t(13)=5.43, p<.01$).

The same 14 participants had an average FLE of 25.8ms in Experiment 2-Sp. This may indicate that for naïve observers of this phenomenon, measurement stability is a question. There was also no counterbalancing between experiments, i.e., the participants always did Experiment 2-Sp before Experiment 2-L. Even though the entire set of experiments took less than an hour to complete, learning or fatigue may have played a role in the observed differences in results.

**Experiment 3-S: Flash-Initiated FLE – Spatial (FIC-S)**

This experiment measured the FLE of the flash-initiated condition. In this configuration, the FLE was measured by moving the flash position to match where the participant observed the initial position of the moving stimulus to be. As such, the direct measure is visual angle (minutes of arc), rather than time (ms) as in Experiments 2-Sp and 2-L. A positive value indicates that the flashed stimulus needed to be shifted in the direction of motion of the moving stimulus, hence flash lag. A $2\times2\times2$ repeated measures
ANOVA was performed examining the effect of the three variables (foveal approach, luminance of moving stimulus, and luminance of flashing stimulus) on flash location. Two main effects reached significance, moving stimulus luminance \( (F(1,14) = 20.69, p = .0005) \) and foveal approach \( (F(1,14) = 8.82, p = .01) \). The interaction between flashing stimulus luminance and foveal approach was near significance \( (F(1,14) = 7.02, p = .019) \).

Because the data failed both Bartlett’s (test statistic = 14.64, \( p = .041 \)) and Levene’s (test statistic = 2.45, \( p = .022 \)) tests for homogeneity of variance, these results must be interpreted with great caution (Figure 16 shows a plot of condition means with standard errors).

The procedure for dealing with non-homogeneity of variance is to test the specific effects of interest, rather than rely on the omnibus test. Hypothesis 2 posits that the lower \( I_{\text{flashing}}/I_{\text{moving}} \) ratio will produce a larger FLE than the higher \( I_{\text{flashing}}/I_{\text{moving}} \) ratio will for CM, but not for the FIC. Directly comparing these conditions (averaging across the 2 foveal approach levels) results in a significant difference \( (t(14) = -4.59, p < .001) \), with the FLE for the higher \( I_{\text{flashing}}/I_{\text{moving}} \) ratio (\( M = 4.3 \) min, \( SD = 8.7 \) min) larger than the FLE for the lower \( I_{\text{flashing}}/I_{\text{moving}} \) ratio (\( M = -3.3 \) min, \( SD = 10.5 \) min). This supports the exception condition in hypothesis 2, which states only that the FIC will not act in the same direction as the CM condition, and it did not. Hypothesis 5 states that no luminance
ratio will negate the FLE. Whereas the FLE is negative (-3.3 min) in the lower I_{\text{flashing}}/I_{\text{moving}} ratio, this value (which averages over the foveal approach levels) is not significantly different from zero. However, if one separates the foveal approach conditions, the specific condition of foveofugal and low I_{\text{flashing}}/I_{\text{moving}} ratio does have a significant flash-lead effect (M = -0.176, SD = .132) (t(14) = -4.22, p < .001), which is contrary to the hypothesis.

Hypothesis 5a says that low I_{\text{moving}} will produce a higher FLE in the FIC spatial paradigm. The 2×2×2 repeated measures ANOVA (flash luminance, moving luminance, foveal approach) showed that there was indeed a large main effect of I_{\text{moving}} (F(1,14) = 20.69, p<.0001; Figure 17). The homogeneity of variance issue is unlikely to negate an effect with this level of significance. To further guard against a spurious result owing to the homogeneity of variance issue, the Wilcoxon signed rank test for the ordered pairs was employed separately for the foveal approach levels owing to the apparent significance of that variable. For the foveofugal level the 1-tail test was significant at α = .05 (z = 2.26, p = .012), with 13 of 15 positive contrasts summing to 100 and two negative contrasts summing to 20. Similarly for the foveopetal level, the 1-tail test was significant at α = .05 (z = 2.88, p = .002), with 13 of 15 positive contrasts summing to 111 and two negative contrasts summing to 9. Hence, the non-parametric test also
showed a significant effect of $I_{moving}$ for both levels of foveal approach, supporting hypothesis 5a. An $\alpha$ of .05 was used for these two non-parametric tests, because the more conservative value of $\alpha$=.01 was guarding against spurious results of omnibus F values due to data replacement as described in the earlier data analysis section. This ordinal pairing test should not be as sensitive to the data manipulations, and the test was specific and testing an a priori hypothesis.

Since there were no significant interactions, dependent samples $t$-tests were conducted for both the foveopetal and foveofugal level, collapsing across the non-significant $I_{flashing}$ variable, using a conservative $\alpha$ (.01) to again control for Type I errors. Both foveal approach levels exceeded this conservative level of significance for a 1-tail dependent samples $t$-test with, the difference between the low and high $I_{moving}$ levels averaging $0.063^\circ$ ($t(14) = 2.75, p = .0078$) for foveofugal approach, and $0.119^\circ$ ($t(14) = 3.79, p = .00099$) for foveopetal, thus showing support for hypothesis 5a.

Noteworthy here are the magnitudes of the actual FLE effects. Table 1 shows the four main effect-dependent FLE values and their standard errors. Although none of these measures are significant at $\alpha$=.01, the nearly significant FLE of $0.177^\circ$ represents a 14.8 ms FLE, at $12^\circ$/s, which is on the very low end of typically reported FLE levels. This

<table>
<thead>
<tr>
<th>Moving Stim Lum</th>
<th>Foveal Approach</th>
<th>Mean (deg)</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 cd/m$^2$</td>
<td>Foveofugal</td>
<td>-.0365</td>
<td>.0376</td>
</tr>
<tr>
<td>242 cd/m$^2$</td>
<td>Foveofugal</td>
<td>-.0995**</td>
<td>.0341</td>
</tr>
<tr>
<td>56 cd/m$^2$</td>
<td>Foveopetal</td>
<td>.1771*</td>
<td>.0635</td>
</tr>
<tr>
<td>242 cd/m$^2$</td>
<td>Foveopetal</td>
<td>.0581</td>
<td>.0684</td>
</tr>
</tbody>
</table>

Table 1. Summary of FIC FLE effects for foveal approach and moving stimulus luminance.

** Flash lead ($t(14) = -2.92, p = .0112$)
* Flash lag ($t(14) = 2.79, p = .0145$)
FLE from the CM FLE, often reported to be the same magnitude (Nijhawan & Khurana (1995); Rizk, Chappell, & Hine (2009); Kanai, Sheth, & Shimojo (2004)). However, there have been dependent dissociations between the FIC and the CMC also reported. Rizk et al. (2009) reported a differential dependence on inter-stimulus distance (FIC greater than CMC), and Öğmen, Patel, Bedell, and Camuz (2004) report differential results with the FIC being less dependent upon the flash luminance than the CMC condition.

**Experiment 3-T: Flash Initiated FLE-Temporal (FIC-T)**

The dependent measure for this experiment was the delay applied to the flash appearance to bring it into subjective temporal coincidence with the appearance of the moving object. Negative values mean that the flash had to appear early (before the moving stimulus); positive values mean it needed to be delayed (appearing after the moving stimulus). After determining that the data passed both Bartlett’s (test statistic = 5.86, $p = .556$) and Levene’s (test statistic = 0.26, $p = .968$) tests for homogeneity of variance, a 2×2×2 repeated measures ANOVA (flash luminance, moving luminance, foveal approach) was performed. This showed no significant main effects for foveal approach.
or for the luminance of the flashed and moving stimuli and no significant interactions, although the 3-way interaction approached significance ($F(1,12) = 5.66, p=.035$).

Temporal delay, when collapsed across conditions ($M = 73.2$ ms, $SE = 48.4$ ms), was significantly different from zero ($t(12) = 5.46, p <.0001$) and positive. This clearly indicates that participants perceived the flash before the moving stimulus, and thus the flash had to physically appear after the moving one in order for the two stimuli to be perceived as temporally coincident.

This experiment specifically addressed hypothesis 6, that stated that the TOJ would be affected by the ratio of $I_{\text{flashing}}/I_{\text{moving}}$ without the consideration of foveal approach, and specifically that a higher $I_{\text{flashing}}/I_{\text{moving}}$ ratio would result in favoring the earlier perception of the flash, and vice versa. The 3-way interaction (Figure 18) approaching significance suggests that this might be pursued further. However, the Wilcoxon signed-rank test performed on the specific high vs. low $I_{\text{flashing}}/I_{\text{moving}}$ ratio data independently for both foveal approach levels failed to show significance. Therefore, there was no support for hypothesis 6.

**Experiment 4-S – Flash-Terminated FLE-Spatial (FTC-S)**

This experiment measured the FLE of the flash terminated paradigm. In this configuration, the FLE was measured by moving the flash position to align it with the

![Figure 19. Interaction plot showing offset as a function of luminance. This effect did not reach significance, but indicates a thread for future research.](image-url)
The final position at which the participant observed the moving stimulus to occupy. Positive values indicate that the flash needed to be moved beyond the final position of the moving stimulus in the direction of motion of the moving stimulus, hence flash lag. Negative values indicate that the flash was displaced to a location behind the final location of the moving stimulus, meaning that the moving stimulus was not perceived to reach its actual terminal point. After determining that the data passed both Bartlett’s (test statistic = 3.63, \( p = .821 \)) and Levene’s (test statistic = 0.56, \( p = .788 \)) tests for homogeneity of variance, a 2x2x2 within subjects ANOVA was performed, examining the effect of the three variables (foveal approach, luminance of moving stimulus, and luminance of flashing stimulus) on flash location. There were neither main effects nor interactions that reached significance. The critically important statistic for this experiment is the FLE measure. Collapsed across all conditions, the FLE measured was -0.139\(^\circ\) (SD = .138). This means that on average the moving stimulus fell short of its terminal point by 8.33 arc-min and this was significantly different from zero (\( t(12) = -3.64, p = .0024 \)). Hypothesis 3 stated that a sufficiently high \( \frac{I_{\text{flashing}}}{I_{\text{moving}}} \) ratio would induce a flash lead effect, whereas these results show that the average effect collapsed over all conditions showed a flash lead. This hypothesis was best evaluated in the interaction of the moving stimulus luminance and flashing stimulus luminance. This interaction failed to reach significance.

![Figure 20. This plot shows the significant main effects of moving luminance and foveal approach on the temporal perceptual precedence of the flashed vs. moving stimulus.](image)
for the fully modified data \((F(1,12) = 4.58, p > .01)\), and neared significance at \(\alpha = .05\) for the unmodified data \((F(1,12) = 4.74, p < .05)\). Examination of the \(I_{\text{flashing}}/I_{\text{moving}}\) interaction plot (Figure 19) shows that there is a possible interaction that could emerge with sufficient statistical power. The specific way that the hypothesis is stated suggests that the flash lead effect would emerge only with sufficiently high levels of \(I_{\text{flashing}}/I_{\text{moving}}\).

Although the specific condition for the flash lead was not supported, the existence of a flash lead at all, was supported.

**Experiment 4-T: Flash-Terminated FLE-Temporal (FTC-T)**

The dependent measure for this experiment was the delay applied to the flash timing to bring its disappearance into subjective temporal coincidence with the disappearance of the moving object. Negative values mean that the flash had to appear early; positive values indicate it needed to be delayed. After determining that the data passed both Bartlett’s (test statistic = 7.46, \(p = .382\)) and Levene’s (test statistic = 1.04, \(p = .412\)) tests for homogeneity of variance, a \(2 \times 2 \times 2\) ANOVA with foveal approach and luminance of the flashed and moving stimuli was performed. It produced no significant main effects or interactions at \(\alpha = .01\), though both moving stimulus luminance \((F(1,12) = 7.36, p = .019)\) and foveal approach \((F(1,12) = 6.19, p = .029)\) neared significance. Figure 20 shows these
‘near significant’ main effects, to point out that all individual conditions have negative values, showing that no case appears to violate the average collapsed across all conditions (M = -.0627, SD = .0393). This means that the flash had to be presented, on average, 62.7 ms before the disappearance of the moving object to achieve subjective simultaneous extinction.

Hypothesis 4 stated that in the FTC paradigm, a high luminance ratio (high $I_{\text{flashing}}/I_{\text{motion}}$) would result in the perception of the flash extinguishing after the moving stimulus and vice versa. This tests the notional (DNL) perceptual priority of the moving stimulus and the effect luminance has on that priority. It was noted above that $I_{\text{moving}}$ approached significance ($p = .019$) with a conservative $\alpha (.01)$. Figure 21 shows the relationship between the individual cells in the 2x2x2 ANOVA analysis. Note that when comparing the high $I_{\text{flashing}}/I_{\text{motion}}$ ratio to the low $I_{\text{flashing}}/I_{\text{motion}}$ ratio separately for the foveal approach conditions (datum 3 vs. 5 and 4 vs. 6), the means are each separated by more than 2 standard errors (pooled). Pooling the errors here is justified because the variance is homogenous. In both cases, the flash is more favored (requiring less temporal advance) in the high $I_{\text{flashing}}/I_{\text{motion}}$ ratio. So while no condition reaches the point of favoring the flash (no point is positive), the direction of the effect is as hypothesized, although not reaching significance with the more conservative criterion.

**Results Experiment Series 2**

**Experiment 1 – Reaction Time**

For the 15 participants who also participated in Experiment 2, the mean reaction time was 208.1 ms ($SD = 15.3$ ms). The data ranged from 185.6 ms to 237.4 ms. All values are for the average of the top five fastest times of the approximately 30
measurements obtained from each observer. These data fall within the expected range of simple reaction times to visual stimuli onsets reported by Carreiro, Haddad, and Baldo (2011) when examining the effect of brightness and positional predictability on RT. Correlation results will be addressed in the next section.

**Experiment 2-L – Continuous-Motion FLE (CM)**

This experiment was similar to Experiment 3 of Series 1. The variable being adjusted was the temporal adjustment applied to the flash in order to bring it into perceptual spatial alignment with the moving stimulus. Negative values indicate that the flash had to appear early to overcome the FLE. Positive values indicate that the flash had to be delayed, indicating a flash lead. After determining that the data passed both Bartlett’s (test statistic = 5.42, \( p = .609 \)) and Levene’s (test statistic = 0.45, \( p = .869 \)) tests for homogeneity of variance, a 2×2×2 repeated measures ANOVA (flash luminance, moving luminance, foveal approach) was performed that produced no significant main or interaction effects (\( \alpha = .01 \)). Additionally, the overall FLE collapsed across all conditions (\( M = .0060, SD = .0404 \)) also was not significantly different from zero (\( t(15) = .60, p > .05 \)).

This experiment addressed the first two hypotheses and the research question regarding the possible covariance of simple RT and FLE. Hypothesis 1 stated that the FLE would be affected by the foveal approach variable. Hypothesis 2 posited that the \( I_{\text{flashing}}/I_{\text{moving}} \) ratio would affect the FLE with a higher ratio reducing the FLE. Neither of these hypotheses was supported.

The research question addressed the possible correlation between simple RT to a visual stimulus onset and the magnitude of the FLE. A regression of the FLE from
Experiment 2 and the RT from Experiment 1 failed to reach significance $r(13) = .158$ (Figure 22), and thus failing to show any support for the FLE-RT relationship. However, the positive values found for FLE (actually a flash lead) were unexpected. Therefore, the analysis was rerun with the subset of data with an FLE. The result for this FLE subset regressed against the median RT rather than the fastest 5 times (Figure 23) was $r(4) = .822, p = .045$. Although this statistic treatment does not provide support of the hypothesis and the strong result is clearly indicative of the ‘z’ product moment of the participants with the strongest FLEs, it is included because it may be sufficiently interesting to suggest further work in an experimental paradigm that ensures traditional FLE results.

**Experiment 3-S – Flash Initiated FLE – Spatial (FIC-S)**

As in Experiment 4 of series 1, the dependent variable of this experiment was the spatial adjustment made to the flashing object to bring it into perceptual spatial alignment with the moving bar. Positive values indicate that a position shift of the flashing stimulus in the direction of motion was necessary for alignment—indicating a perceptual flash lag. After determining that the data passed both Bartlett’s (test statistic = 9.55, $p = .215$) and Levene’s (test statistic = 0.78, $p = .602$) tests for homogeneity of variance, a within-
was performed for the 17 participants in this experiment at $\alpha = .01$. Of the three possible main effects, both the moving bar luminance ($F(1,16) = 31.0, p < .0001$) and the foveopetal/foveofugal contrast ($F(1,16) = 26.7, p < .0001$) were significant. The effect of the flashing bar luminance was not significant. The interaction of the moving bar luminance and the foveal approach also were significant ($F(1,16) = 11.9, p < .01$). Figure 24 shows the main effect and interaction and is shown with standard error bars.

The four individual condition values are each significantly different than zero and are positive, and just as in the analogous experiment in Series 1, indicate that there is a flash lag effect ranging from 0.11 deg (6.8 arc-min) for the bright stimuli moving in the foveofugal direction to .63 deg (37.5 arc-min) for dim stimuli moving in the foveopetal direction.
This FIC spatial FLE experiment addressed hypotheses 2, 5, and 5a. Hypothesis 2 predicts that the FLE will be greater for low $I_{\text{flashing}}/I_{\text{moving}}$ than for high $I_{\text{flashing}}/I_{\text{moving}}$ for the CM configuration, but not the FIC or FTC configuration. Figure 25 shows that the brighter moving stimulus does not have a greater FLE than the dimmer one, supporting hypothesis 2. Hypothesis 5 states that even the least favorable FLE conditions in the FIC paradigm will nevertheless have a significant FLE. Given that the 3-way interaction approached significance ($F(1,16) = 6.59, p = .021$), it seemed most conservative to not pool. The lowest value of FLE for these conditions is 0.119° and this is greater than 3 standard errors (3.337 std errors) from 0, clearly different from zero.

Hypothesis 5a predicts differential involvement of the moving and flashing stimuli with regard to their luminance levels. Specifically, the moving stimulus should affect the FLE (with high $I_{\text{moving}}$ producing less FLE), while $I_{\text{flashing}}$ should not. This hypothesis was completely supported with the significant main effect for $I_{\text{moving}}$ reported above and the lack of an effect for $I_{\text{flashing}}$.

**Experiment 3-T: Flash-Initiated FLE – Temporal (FIC-T)**

The variable of interest here was the temporal delay required to produce subjective simultaneity of appearance of the flash and moving stimuli. Positive numbers mean that the flash had to be delayed (appearing after the moving stimulus) to create subjective simultaneity of appearance. After determining that the data passed both Bartlett’s (test statistic = 1.68, $p = .975$) and Levene’s (test statistic = 0.31, $p = .948$) tests for homogeneity of variance, a 2×2×2 repeated measures ANOVA (flash luminance, moving luminance, foveal approach) was performed. The only main effect of significance was foveal approach ($F(1,17) = 10.6, p = .005$) and there were no significant
interactions. The flash delay was greater for the foveofugal condition (M = 66.9 ms, SD = 30.4 ms) than the foveopetal condition (M = 56.6 ms, SD = 30.1 ms). Both levels of the foveal approach variable were significantly larger than zero (t(17) = 7.98, p < .0001 for foveopetal and t(17) = 9.35, p < .0001 for foveofugal), meaning that the flashed bar was seen before the moving bar in all cases by about 61 ms. This outcome is quite comparable to the 73.2 ms found in Experiment Series 1.

This experiment addressed hypothesis 6, which was that the combination of a high luminance flashing stimulus and a low luminance moving stimulus (high I_{flashing}/I_{moving}) will produce a temporal order judgment favoring the flash compared to the reverse (high moving and dim flashing). This effect could manifest as a main effect of either of the stimuli luminance factors or, more likely, as an interaction between them. Also possible would be the 3-way interaction involving the foveal approach factor. None of these was significant or even approached significance. Examination of the individual cell means (Figure 26) shows the relationships among the conditions. The maximum latency difference was seen between the high and low I_{flashing}/I_{moving} conditions, which was expected. These differences, for the petal and fugal levels of foveal approach, were 4.6 ms and 10.7 ms, respectively. These values are in the same order of magnitude as the latency difference (~8 ms) computed by Mojon et al. (1994) when using a 20%
transmissive neutral density filter to measure the Mach-Dvorak effect (discussed in the Introduction). While the hypothesis was not statistically supported, it appears that the high level of variability in the data may be the problem, rather than the magnitude.

**Experiment 4-S: Flash-Terminated Condition Spatial Flash Lag**

The dependent variable in this experiment was the positional offset applied to the flashed stimulus to produce subjective equivalence (alignment) with the last visible position of the moving bar before its disappearance. The flashed and moving stimulus disappeared simultaneously. Positive values indicate that the flashed stimulus had to be shifted in the direction of motion (going beyond the moving stimulus) and negative values indicate shifts in the upstream direction, meaning that the moving stimulus did not perceptually reach the actual position of disappearance.

After determining that the data passed both Bartlett’s (test statistic = 9.55, \( p = .215 \)) and Levene’s (test statistic = 0.78, \( p = .602 \)) tests for homogeneity of variance, a within-subjects 2×2×2 factorial repeated measures ANOVA (flash luminance, moving luminance, foveal approach) was performed on data from 16 participants. Of the three possible main effects, only the petal-fugal contrast reached significance (\( F(1,15) = 15.72, \ p = .001 \)). There were no significant interactions, although the flashing stimulus luminance – foveal approach interaction approached significance (\( F(1,15) = 6.64, \ p = .021 \)). Both of the foveal approach conditions resulted in PSEs corresponding to subjective disappearance of the moving stimulus short of the actual point of disappearance, with the foveofugal level averaging 12.7 arc-min (SD = 5.42 arc-min) and the foveopetal level 9.4 arc-min (SD = 6.26 arc-min). Each of these values was compared to zero with one-sample \( t \)-tests, collapsing across the luminance levels. For the
foveofugal level $t(15) = 9.40, p<.0001$ and for the foveopetal level $t(15) = 5.99, p<.0001$.

In the first experimental series, there was no foveal approach main effect, but the overall effect was 8.3 arc-min in the same direction as these results. All the FTC spatial results were quite consistent, with the moving stimulus perceptually not reaching the actual point of termination.

Hypothesis 3 stated that a sufficiently high $I_{\text{flashing}}/I_{\text{moving}}$ would induce a flash lead effect. The notion of a flash lead being attainable (moving stimulus failing to reach a perceptual endpoint) was supported, but it was so in all tested values of $I_{\text{flashing}}/I_{\text{moving}}$. The dependence on foveal approach is clear in Figure 27, as is the fact that there was nothing close to a veridical point of subjective disappearance. The hypothesized dependence of the effect on $I_{\text{flashing}}/I_{\text{moving}}$ was not supported.

**Experiment 4-T: Flash-Terminated FLE-Temporal (FTC-T/TOJ)**

The dependent variable in this experiment was the temporal offset applied to the disappearance of the flashing object with respect to the disappearance of the moving bar to produce subjective simultaneity of disappearance of both bars. Negative values indicate that the flashing bar disappeared earlier than the moving bar, meaning it took longer for the flash to reach its perceptual termination. After determining that the data
passed both Bartlett’s (test statistic = 10.18, \( p = .178 \)) and Levene’s (test statistic = 1.24, \( p = .288 \)) tests for homogeneity of variance, a within-subjects 2×2×2 factorial repeated measures ANOVA (flash luminance, moving luminance, foveal approach) was performed using data from 16 participants in this experiment. None of the effects were significant; however, all three main effects approached significance, as did the interaction between the luminance levels of the flashing and moving stimuli.

Collapsed across all variables, participants saw the disappearance veridically, as there was no significant difference between the average (\( M = 0.00 \text{ ms}, \text{SD} = 27.8 \text{ ms} \)) required delay, and zero. This is quite different from the 62 ms flash acceleration that was required in Experiment Series One, and at this conservative criterion failed to show support for hypothesis 4, that states that in the FTC paradigm, the luminance ratio \( (I_{\text{flashing}}/I_{\text{motion}}) \) would significantly affect the TOJ. However, examining the interaction plot (Figure 28), it is observed that the comparison of the bright \( I_{\text{flashing}}/I_{\text{motion}} \) condition and the dim \( I_{\text{flashing}}/I_{\text{motion}} \) condition shows that they are different by more than two standard errors, and that the bright \( I_{\text{flashing}}/I_{\text{motion}} \) condition requires more flash delay (favoring the flash) than the dim \( I_{\text{flashing}}/I_{\text{motion}} \) condition. This is doubtless explained by
all the relevant variables approaching significance. With a less conservative criterion (.05 vs. .01), this hypothesis would be supported.

**Experiment Series One Discussion**

Taken together, the first two experiments explored the possibility that there is a relationship between the FLE and RT. Due to neural transmission delays, the perceptual system operates in the past. While this delay is variable, depending on the specifics of the percept, motion perception is at least 40 ms behind the physical stimulus and perhaps as much as 100 ms (Nijhawan, 1994). In re-introducing the FLE, Nijhawan (1994) suggested that there must be some way in which the neural lag is being compensated since animals, including humans, have extraordinary intercept capabilities. If some or all of the compensation happens in the visual system, then there must be some temporal displacement for moving objects brought about by lateral connections of retinotopically arranged cortical areas. For moving stimuli, this advantage (once established) would

![Figure 29. The left panel shows the linear regression between the foveofugal and foveopetal levels with all data included. Removal of the five apparently anomalous data points in the lower right of A yields the relationship shown in B with a much higher correlation.](image)

result in an object being seen along its trajectory veridically, i.e., ahead of its neurally lagged position, while a flashed stimulus would still suffer the uncompensated-for perceptual delay. This would result in the flashed stimulus lagging behind a moving object in a simultaneous presentation. If a neural compensatory feed forward or
extrapolative mechanism is operational within the visual system, it is possible that it could be observed in the relationship between reaction time and FLE. Observers with lower RTs should have a smaller FLE (more positive delay number in these experiments) because there would be less compensatory need to effect a successful intercept. This predicts a positive association of RT with FLE. Because of the main effect in foveal approach, the correlations were split into separate foveopetal and foveofugal analyses, however neither showed significance. Though non-significant, the correlations themselves were directionally correct, meaning that higher RTs produced generally larger FLEs. Further examination of the data revealed that just a subset of the participants showed an FLE at all—a surprising outcome given the robustness of the effect when measured by investigators using generally small ‘n’ studies of experienced observers. A scatterplot of the two foveal approach conditions showed that several participants’ data were outliers in an otherwise coherent relationship between the foveopetal and foveofugal conditions.

In Figure 29A, the five points on the lower right are certainly suspect as measurement anomalies. Removal of these five points (Figure 29B) changes the picture entirely, changing the petal-fugal correlation from a non-significant 0.11 to strong and significant 0.69. However, the removal of these suspect measurements still did not reveal a latent relationship between FLE and RT. Note here that the direction of motion was randomly varied (L-R & R-L) in order to suppress possible MAE issues. Data were not separable by direction of motion.

If one accepts, given the robust history of FLE experiments, that in the CM condition all observers should have shown some FLE, a final check of the relationship
between RT and the stronger foveopetal FLE was made by removing all null flash lag observations. The justification of this approach would be that fully trained observers would have a typical distribution of RTs, but always measure some level of FLE. This certainly could be verified with a protocol that included a significant training cycle preceding data collection. Removing all non-FLE observations retained 31 data points and resulted in significant ($r(29) = .416, p<.05$) correlation. The higher $\alpha$ was used here because the data-replacement protocol was not a factor and no substantive conclusion is being made based upon the finding. Figure 30 shows this relationship of increasing RT with increasing FLE, as one would predict. This relationship, if borne out in future experiments, could help explain individual differences in FLE. However, RT was used here as an accessible surrogate for the actual variable of interest, visual information transmission time to the visual cortex. Reaction time is inherently noisy by comparison to a more direct measure of neural transmission time because of systematic individual motor response variability and performance factors such as attention and motivation. Further studies would be better served with a more direct method that mitigated these sources of error.

In Experiment 2-L the continuous motion paradigm was again tested with the foveal approach condition, but this time the luminance level of the moving and flashing

Figure 30. Linear regression between foveopetal FLE and RT shows a significant positive relationship.
stimuli were varied instead of speed as in Experiment 2-Sp. Here, although an overall 54 ms FLE was exhibited, there were no main effects significant at the .01 level. Given the level of general robustness of the foveal approach factor, this is surprising. However, the flash luminance was significant in the raw data and approached significance ($p = .03$) on the modified data. It is quite possible that an ‘n’ of 13 simply did not provide sufficient statistical power. Collapsed across other variables, the dim ($56 \text{ cd/m}^2$) flash luminance conditions ($M=60.1 \text{ ms, SD} = 38.9 \text{ ms}$) produced a larger FLE than the bright ($242 \text{ cd/m}^2$) flash luminance conditions ($M=48.0 \text{ ms, SD} = 37.9 \text{ ms}$). Based solely upon how Baldo and Caticha’s (2005) model accumulates activity over time (as well as discussion about leaky integrators, below), one would expect that a dimmer flash would take longer to reach a perceptual endpoint and this result is consistent with that. Baldo and Caticha’s model predicts that the luminance ratio between the moving object and the flashing object is a significant predictor of FLE levels, and is consistent with theories that differential neural latencies are, at the very least, operational in the CM FLE paradigms even if not sufficient to explain all observations. For example, Arnold, Durant, and Johnston (2003) conclude that DNL favors the moving stimulus by 20ms, which would moderate, but not explain, the FLE. Arnold, Ong, and Roseboom (2009) used a comparison of position and color feature in an FLE paradigm with latencies introduced by contrast changes to again argue that the FLE was modulated but not produced by DNL. Whitney, Murakami, and Cavanagh (2000) suggested that the FLE is DNL based, if only because they had eliminated contending contemporaneous theories such as extrapolation (Nijhawan, 1994).
A critical prediction of the Baldo and Caticha model is that the FLE for the flash-initiated condition (FIC) is based upon a mechanism that is spatial and not temporal. This clearly distinguishes it from the differential latency model, which is inherently temporal, or the postdiction model, which uses spatiotemporal averaging. To demonstrate this, the FIC experiments measured the temporal advantage between the moving and flashing stimuli in Experiment 3-T and the spatial FLE in Experiment 3-S. In Experiment 3-T, the temporal advantage of the flash was both statistically significant and quite large in the context of FLE effects. The average advantage was 73 ms in favor of the flash. This perceptual advantage of the flash is a remarkable and contradictory outcome given that the FLE is based upon the flash perceptually lagging behind the moving stimulus. The spatial results showed dependence on foveal approach and the luminance of the moving stimulus. The foveopetal approach produced a larger FLE than the foveofugal approach, which actually showed a significant flash lead of 6 arc-min coupled with the brighter moving stimulus. The dimmer moving stimulus showed a 10.6 arc-min FLE. The effect of a brighter moving stimulus was consistent between foveal approach conditions, producing either a smaller FLE, or larger flash lead. The Baldo and Caticha model predicts exactly this, because in the FIC the percept will originate nearer the veridical position when brighter. This model is a three-level neural network, with input, hidden, and output layers. The physiological analog would be a leaky-integrate and fire model of neural activity. It clearly makes sense that a brighter stimulus would accumulate to the neural firing threshold more quickly than a dimmer one. This necessarily means that for a brighter stimulus, a shorter distance would be traversed before the output layer reached its perceptual threshold. These results are completely
consistent with that model. Moreover, taken with the results of a temporal advantage of
the flash, the results show that differential percept timing of the flash and the moving
stimuli cannot be the explanation for the FIC FLE. While this pair of experiments does
not rule out DNL as explanatory in the case of the CM paradigm, it negates it for the FIC.
In the case of postdiction, the theory is that the flash ‘resets’ the spatiotemporal
integrator. Given the complexity of the visual apparatus, it is unclear whether this reset is
phenomenal or not (i.e., does the reset depend on an actual percept of the flash?). If it
does, these results clearly argue against a postdiction model that integrates position over
some tens of milliseconds, given that the flash percept was 73 ms ahead of the moving
stimulus percept. Neither is there any reason to believe that there is any cueing or other
attention biasing mechanism. The motion bias model, a modified form of postdiction,
also requires that there is a moving stimulus present to create the bias. This is present in
FIC, of course. Eagleman and Sejnowski (2007) argue that the moving stimulus is
‘autobiasing’ because the motion of the moving stimulus alone can create it, just as in the
Fröhlich effect that has no flash. Given the comparative huge temporal advantage of the
flash, motion bias based upon the timing of the flash would also seem to be ruled out.

Taken together, Experiments 3-S and 4-S create significant difficulty for DNL,
postdiction, and attention. Motion bias, on the other hand, can explain these results if one
assumes, as Eagleman and Sejnowski do, that the Fröhlich effect is a special case of the
FIC with no requirement for the flash. Additionally, Baldo and Caticha’s neural model is
well supported, because it predicts that the first stimulus perception will be
‘downstream’ of its origination due to spatial effects that are disconnected from temporal
effects. There has been no discussion within motion bias about the possible effects of
stimulus luminance. The neural mechanism proposed (Eagleman & Sejnowski, 2007) suggests that there could be feedback from the motion processing center(s) (Nishida & Johnston, 1999) or asymmetric connections within V1 (Fu, Shen, Gao, & Dan, 2004). Of course, these are not mutually exclusive. Either of these portends possible luminance dependence, because the biasing outcome could be dependent on the ‘state’ of V1 in conjunction with any interacting signals. Within the temporal domain limits of the FLE, both the strength and timing of all the signals could be affected by signal luminance. In fact, Sundberg, Fallah, and Reynolds (2006) argue that position ultimately is describable as a Bayesian probability density function. Brighter signals get to their destination sooner and garner more PDF weight. In this way motion bias and the Baldo and Caticha’s model possibly agree.

The flash-terminated experiment (FTC), Experiment 4-S, was used to test Baldo and Caticha’s model in a different way and help to differentiate it from previous models. In the FTC, the moving stimulus disappears simultaneously with the termination of the flash, and the flash position is adjusted to bring them into subjective spatial alignment. Previous experimental results using FTC were used to argue against an extrapolative model for FLE, because the results showed veridical alignment of the stimuli. The extrapolative mechanism would act as if one were wearing a prism to compensate for neural lag. A lack of a moving stimulus overshoot argues against this type of perceptual indexing. The postdiction model, spatiotemporal integration for some period after the flash, could explain this result because the only position that the moving stimulus would ever occupy during and after the flash is the last frame it occupied. Hence, postdiction predicts that there should be veridical alignment in the FTC. The neural latency model
would predict that the moving stimulus would reach its terminus temporally before the flash, but not be spatially misaligned. In Baldo and Caticha’s model, the output layer of the model is driven by the relationship of the inputs (five in the model, but realistically many) of the hidden layer and the decay rate of the accumulator for each location. This means that a moving stimulus is providing excitation for positions on either side of its present position. The output layer accumulates all these signals over a time period depending on the decay rate. Therefore for at least some combinations of input strength, connection strength, movement rate, and decay rate, the moving stimulus would not drive the output layer to threshold at any given position until it was past that position. The output layer would be, therefore, spatially behind the moving stimulus. This phenomenon is crucial to their argument that for the FIC, the first position to be driven to threshold cannot be the initiating position, because there were no antecedent excitations. However, that same arrangement results in a ‘premature’ extinction if the moving stimulus suddenly disappears. This fact sets up the possibility that extinguishing the stimulus from the input layer at any given position would prevent the signal in the output layer from ever reaching that same position, because there would be no input from subsequent positions. Perceptually, the prediction would therefore be that the final perceived position of the moving stimulus would be ‘short’ of the actual point of disappearance and that the flashing stimulus would have to be moved ‘upstream’ from the veridical point to create perceptual alignment. The result of the spatial FTC experiment was that the moving stimulus was perceived to disappear 8.33 arc-min short of its actual termination point. This is consistent with the prediction that there would not be a veridical position percept, and that the moving stimulus would fall short of its actual
final position. As the stimulus was moving at 12°/sec or 720 arc-min/sec (0.72 arc-min/ms), this distance just represents 11.6 ms of movement time. On the other hand, the result of the temporal component of the FTC experiment showed that the flash had to be accelerated by 62.7 ms to create subjective simultaneity of disappearance. Thus, independent spatial and temporal findings suggest, as was true in the FIC experiments, that spatial and temporal properties of the FLE are separable, and must be accommodated within Baldo and Caticha’s model. The acceleration of the flash in the temporal experiment means that the moving object’s disappearance did indeed temporally lead the flash, once motion had been established. Remember that the flash led the moving stimulus in the FIC condition. This argues that neural latency effects could impact perception under some conditions. Arnold et al. (2009) have argued that differential latency effects modified but did not cause FLE. The present finding could support that view.

**Experiment Series Two Discussion**

The second series of experiments was designed to replicate the first, but eliminate the suspect procedural issues that led to data concerns there. However, the overall intent of this series of experiments remained the same.

Experiment 1 in this series was again a reaction time test. The overall RT was similar to the first series at 208 ms. As was true with the first series, there was no significant relationship between FLE and RT. However, there are two factors that make this worth pursuing further, which will be elaborated after the following discussion of Experiment 2-L.
Experiment 2-L in this series varied the luminance of both stimuli and foveal approach. None of the three variables reached significance. Moreover, when collapsed across all variables, the overall FLE was not significantly different from zero. This finding was not at all expected, warranting further exploration. It is possible that the elongation of the moving stimulus along the motion axis due to motion smear is partly responsible for the difference between leading edge and trailing edge FLE observations.

The moving stimulus necessarily blurs as it moves across the retina, but not quantitatively, as much as the visual persistence of integration times might anticipate. If one estimates the blur ensuing in this experiment based on a 120 ms integration time and a stimulus speed of 12°/sec, the trailing blur would stretch back 1.44° (86 arc-min). This would effectively triple the perceived width of the moving bar. In contrast, Burr (1980) measured blur as a function of speed and stimulus duration. There was a nonlinear dependence on stimulus display duration, and a monotonic but unclear increase in blur with speed based on two observers. Using Burr’s results, the expected blur would be in the range of not more than 10 arc-minutes, which at 12°/sec would result in a difference of only about 14 ms of FLE between the leading and trailing edges compared to a stationary flash. Whereas Burr’s results show significant conditional variability, his results suggest that the visual system suppresses perhaps more than 90% of the possible
(based upon integration time) blur. The level of FLE suppression indicated in Burr’s work would not explain the complete elimination of FLE for trailing edge observations. Bedell and Patel (2005) measured the level of motion smear for fixation as part of an investigation of the smear suppression during vestibulo-ocular reflex. While there were significant individual differences (ranging from 25 ms to 125 ms) the average median (per observer) motion smear was 75 ms, easily enough to eliminate the typically observed FLE.

The range of average FLEs by person across all conditions in this experiment was from 68 ms of flash lag to 74 ms of flash lead. The individual results by person by condition ranged from 101 ms flash lag to 121 ms flash lead in an approximately normal distribution (Figure 31), spread across this range (M = .009 , SD = 44).

This finding, which was based on data that included 4 non-naïve participants and 11 naïve participants can only be partially explained by the blur phenomenon directly. The two most experienced observers, who were also the most knowledgeable of the phenomenon (my advisor and myself), produced typical FLE results. It is possible that comparatively less-experienced observers simply had difficulty making the judgment based on the trailing edge (because the leading edge was easier to use or more salient) or had difficulty localizing the trailing edge (criterion variability). The question as to whether the shape distortion due to blurring contributed to the leading edge-trailing edge FLE disparity was comprehensively addressed by Watanabe, Nijhawan, Khurana, and Shimojo (2001). Their study examined the FLE of leading and trailing bars, square-annuli and the leading and trailing edges of a rectangle, while controlling for the perceptual direction-of-motion dilation. Their stimuli were somewhat different from
those used in the present work in that the bars were 1.92° tall x .168° thick. This is an aspect ratio of 11.4:1 compared to 50:1 in the first set of experiments series and 5:1 in the second set of experiments of the present work. Their translation speed was 7.2 °/sec, which is well within the range of speed independence found both here and generally in the FLE literature. However, their stimuli were 2.88° eccentric from the fixation point, whereas the present experiments purposefully had the stimuli within 1° of visual angle of the fixation. Linares, López-Moliner, and Johnston (2007) showed that there is a significant FLE dependence on eccentricity consistent with increasing field sizes with increasing eccentricity. Watanabe et al. (2001) showed quite dramatically that there is a reliable FLE difference (with 6 observers and 20 repetitions per plotted point) when observers make judgments using the leading versus trailing positions, whether the stimuli were discrete bars or edges in a single wider bar (aspect ratio varied around 1:1). In fact, the single wide bar had a ‘negative’ FLE on the trailing edge (10 arc-min of flash lead), while having a 20 arc-min FLE on the leading edge. Linares et al. posit that the negative FLE was an artifact of the instructions, but note the significance of the magnitude of the
leading-trailing difference. In an effort to determine whether the leading edge was affecting the trailing edge or vice-versa, they ran a single bar using the same paradigm. Their single thin bar (aspect ratio of 11.4:1) behaved like the trailing bar in the configurations with two bars translating in parallel. These results suggest that the present null result when examining the FLE of the trailing edge of a bar is not altogether surprising. Moreover, these results suggest very strongly that any measured FLE using the trailing edges of moving bars is inherently conservative, at least in the CM paradigm, making the balance of the spatial FLE observations in Experiments 3-S and 4-S conservative by extension.

The relationship between FLE and RT was examined using a correlation approach. As with series 1, there was no significant correlation between the trailing edge FLE and RT as measured by the top 5 RT measurements, \( r = .16 \). However, when using the median RT instead of the fastest times, \( r \) increased to .31. With only 13 df, this does not approach significance, but the scatterplot of median RT vs. FLE shows that there is an outlier datum (see red circled datum in Figure 32a). Removal of this single datum results in a near-significant \( R^2 \) of .251. These results suggest that further work might elucidate a modest relationship here.

Experiments 3 and 4 in the second experimental set explored the relationship between temporal and spatial effects in the flash-initiated condition (FIC). Recall in the first series that the timing advantage went to the flashing stimulus by 73.2 ms and yet

![Figure 33. Data from Series 2, Experiment 3 FIC-S. FLE dependencies shown upon foveal approach and moving stimulus luminance.](image)
there was a conditionally dependent FLE that showed the typical percep that the flash lagged the moving stimulus in the combination of foveopetal and dim moving stimulus condition. In the second series, the flash again had a timing advantage (66.9 ms in the foveofugal conditions and 56.6 ms in the foveopetal conditions). The spatial FLE for the second series was also conditionally dependent (Figure 33), but in this case every condition showed the typical FLE, with brighter moving stimuli showing less than dimmer (consistent with Experiment Series 1) and foveopetal conditions more FLE than foveofugal. The results of the first and second series’ of experiments are qualitatively almost identical and together show support for the disconnect between the temporal advantage that the flashing stimulus has over the moving stimulus and the FLE. Moreover, the results of the Experiment 2-L in the second series showed no FLE in the traditional CM paradigm. While perhaps surprising, this result certainly argues that this experimental paradigm is somewhat conservative in terms of its quantification of the FLE, allowing these two arguments: The first is that finding an FLE in the FIC is not an artifact of the paradigm, and the second is that the FLE found in the FIC is mechanistically different than in the CM paradigm.

Experiments 4-S and 4-T were conducted using the FTC paradigm, again exploring the relationship between spatial and temporal effects. Hypothesis 3 stated that the moving stimulus would perceptually disappear prior to the actual point of disappearance irrespective of percept timing. The results supported this hypothesis with both the foveofugal (12.7 arc-min) and foveopetal (9.4 arc-min) approach conditions leading to the moving stimulus falling perceptually short of the actual disappearance
point, while the temporal judgment was veridical, again providing evidence that spatial and temporal judgments are independent for certain FLE paradigms.

The following provides a summary of the results as they pertain to each of the hypotheses.

**Hypothesis 1**

When examining the spatial phenomena of the FLE, there will be an effect upon the FLE magnitude of the foveal approach level (foveopetal vs. foveofugal) such that the $\text{FLE}_{\text{petal}} > \text{FLE}_{\text{fugal}}$, except for the FIC and FTC spatial experiments, wherein the spatial-only mechanism precludes the temporal advantage of foveofugal motion is moot.

There were seven separate experimental protocols measuring FLE with two foveal approach levels. Table 2 summarizes these results.

<table>
<thead>
<tr>
<th>Series</th>
<th>Experiment</th>
<th>Description</th>
<th>Statistical Result Foveal Approach Main Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2</strong></td>
<td>3-S</td>
<td>FIC-S</td>
<td>$F(1,14) = 26.7, p &lt; .0001$</td>
</tr>
<tr>
<td>2</td>
<td>4-S</td>
<td>FTC-S</td>
<td>$F(1,15) = 6.64, p = .021$</td>
</tr>
<tr>
<td></td>
<td><strong>Significant at $\alpha = .01$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>2</strong></td>
<td>3-S</td>
<td>FIC-S</td>
<td>$F(1,15) = 8.82, p &lt; .01$</td>
</tr>
<tr>
<td>4</td>
<td>2-L</td>
<td>CM – Lum</td>
<td>$F(1,13) = 0.95, p &gt; .05$</td>
</tr>
<tr>
<td></td>
<td><strong>Significant at $\alpha = .01$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2-Sp</td>
<td>CM – Speed</td>
<td>$F(1,41) = 11.6, p &lt; .001$</td>
</tr>
<tr>
<td>1</td>
<td>2-L</td>
<td>CM – Lum</td>
<td>$F(1,13) = 0.72, p &gt; .05$</td>
</tr>
<tr>
<td></td>
<td><strong>Significant at $\alpha = .05$</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Summary of foveal approach results, all spatial experiments, both series.

The results here are mixed. First, there is no a priori reason for the difference between the first two results. The foveal approach variable was the same, as was the experimental paradigm. The only difference is individual differences in the subset of participants from Experiment 1 who ran Experiment 2-L. Performing an ANOVA on the Experiment 1 subset of data using only the 14 participants from the second, a non-significant result is also obtained ($F(1,13) = 1.99, p > .05$). The most parsimonious
explanations for the difference in the results between item 1 and 2 are, therefore, sampling error of the Experiment 2-L observers and/or the smaller statistical power of Experiment 2-L.

The last CM paradigm petal-fugal measure was in series 2 (Table 2, item 5), where trailing edge judgments were made and therefore may not be directly comparable. Nevertheless, there was no significant effect of foveal approach measured here. In Watanabe et al. (2001), the leading-trailing contrast results showed that the FLE either disappeared or was much reduced in trailing edge observations. The combination of the elimination of the FLE and the effect of foveal approach on the FLE implies that the trailing edge observation could be a different phenomenon than the leading edge. If the difference between leading and trailing was simply a shift in magnitude, effects upon it should remain. The elimination of both suggests that the CM-FLE phenomenon differs with trailing edge observations, or perhaps is eliminated completely.

Most interesting here is that in both single-line (Series 1) and trailing edge (Series 2) observations, there was a significant petal-fugal difference for the FIC, even though the specific magnitude of the FLE was substantially different between the series. In both cases, motion in the foveofugal direction (motion away from the fovea) showed a lower FLE than motion in the foveopetal direction (motion toward the fovea), which is consistent with Shi and Nijhawan (2008). A possible mechanism that could account for these observations is one where there is positional displacement toward the fovea (Changizi, Hsieh, Nijhawan Kanai, & Shimojo, 2008; Shi & Nijhawan, 2012) is additive with motion in the foveopetal direction and countervailing in the foveofugal direction. The present work did not consider absolute positions of the flashed and moving stimuli,
such that only the relative flashing-moving relationship was measured. It is certainly possible that the flash and the moving stimuli are affected differentially, which Changizi et al. argue is part of the mechanism of neural delay compensation.

The FIC-S Series 1 result actually showed a significant FLE only in the combination of a bright moving stimulus and the foveopetal motion, and a flash lead in the opposite case of dim moving stimulus and foveofugal motion. This is different from in the Series 2 FIC-S where all combinations of moving stimulus luminance and foveal approach conditions showed significant FLE. Again, given the propensity for sampling error shown within the present work, it is unclear whether this is due to stimuli differences (wide vs. narrow bars) or the trailing edge phenomenon. Despite that, however, the petal-fugal contrast in some form was evidenced in both experiment series.

Within the FTC paradigm, there were no significant petal-fugal effects, although the effect approached significance in the second series, judging the trailing edge of wide stimuli. The question here is whether the FTC should produce different results than either the FIC or CM. The difference between the FTC and the other two paradigms is that the forward-spreading excitatory cascade, as proposed by the Baldo and Caticha model, is not built upon further after the flashed stimulus appears (and disappears). The difference between the build up on the foveal side of the object’s position and the anti-foveal side therefore becomes moot, as long as the peak magnitude of the cascade remains subthreshold. This would explain the differential effects between the FTC condition and either the FIC or the CM (see Kanai et al.’s (2004) asymmetric spread account, pp. 2616).
Hypothesis 2

In all FLE spatial paradigms, the ratio of the stimuli luminance was tested for its effect on FLE magnitude. Specifically, the combination of a high luminance flashing stimulus and low luminance moving stimulus was predicted to produce a smaller FLE than the reverse—a low luminance flashing stimulus and high luminance moving stimulus, for the CM paradigm only.

The specific contrast specified in the hypothesis might be found in the interaction between $I_{\text{flashing}}$ and $I_{\text{moving}}$ in the ANOVAs of the spatial experiments. The summary of these results is given in Table 3.

<table>
<thead>
<tr>
<th>Series</th>
<th>Experiment</th>
<th>Description</th>
<th>Statistical Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-L</td>
<td>CM – Lum</td>
<td>$F(1,13) = 0.38$, $p &gt; .05$</td>
</tr>
<tr>
<td>1</td>
<td>3-S</td>
<td>FIC-spatial</td>
<td>$F(1,14) = 1.60$, $p &gt; .05$</td>
</tr>
<tr>
<td>1</td>
<td>3-S</td>
<td>FTC-spatial</td>
<td>$F(1,12) = 4.58$, $p &gt; .05$</td>
</tr>
<tr>
<td>2</td>
<td>2-L</td>
<td>CM – Lum</td>
<td>$F(1,15) = 0.46$, $p &gt; .05$</td>
</tr>
<tr>
<td>* 2</td>
<td>3-S</td>
<td>FIC-spatial</td>
<td>$F(1,16) = 8.1$, $p = .012$</td>
</tr>
<tr>
<td>2</td>
<td>4-S</td>
<td>FTC-spatial</td>
<td>$F(1,15) = 0.04$, $p &gt; .05$</td>
</tr>
</tbody>
</table>

* Significant at .05
Table 3. Summary of $I_{\text{flashing}}/I_{\text{moving}}$ interactions, all spatial experiments, both series.

However, because there was an a priori prediction that compared specific

| Series | Experiment | Description     | Statistical Result | |
|--------|------------|-----------------|--------------------|
| * 1    | 2-L        | CM – Lum        | $t(13) = 2.69$, $p < .01$ (1t) |
| * 1    | 3-S        | FIC-spatial     | $t(14) = 4.59$, $p < .01$ (1t) |
| 1      | 4-S        | FTC-spatial     | $t(12) = 1.25$, $p > .05$ |
| 2      | 2-L        | CM – Lum        | $t(15) = 0.88$, $p > .05$ |
| * 2    | 3-S        | FIC-spatial     | $t(16) = 2.70$, $p < .01$ (1t) |
| 2      | 4-S        | FTC-spatial     | $t(15) = 0.28$, $p > .05$ |

* Significant at .01, 1 tailed dependent samples
Table 4. Summary of $I_{\text{flashing}}/I_{\text{moving}}$ t-tests, all spatial experiments, both series.
confounded conditions, it is reasonable to directly test these with dependent samples t-
tests. Table 4 shows the results of this analysis.

In Series 1 Experiment 2-L (CM), the results showed that a larger FLE (by 21ms) was obtained in the high $I_{\text{moving}}/I_{\text{flashing}}$ conditions relative to the low $I_{\text{moving}}/I_{\text{flashing}}$ conditions. However, as predicted the FIC and FTC paradigms were not similarly affected and indeed, the FIC-S paradigms showed the reverse. A higher FLE was shown in the lower $I_{\text{moving}}/I_{\text{flashing}}$ conditions. This argues very strongly that the fundamental phenomenology is different for the FIC than the CM. Whereas one cannot measure which stimulus is seen first in the CM paradigm, which is seen first is measureable in the FIC. In both series, the flash was seen first in the FIC by tens of milliseconds. Again, this argues that no temporal advantage argument can be made in the FIC, regardless of how compelling the evidence might be in the CM – again arguing for a different mechanism in the FIC compared to the CM. The hypothesis only stated that the CM paradigm would show this luminance ratio effect, therefore the lack of a result for the FTC paradigm is supportive. The only one of the six outcomes that is nonsupportive is the CM in Series 2 (Experiment 2-L). This null result is nonsupportive. However, this experiment and others (e.g., Chung et al., 2007) have shown that the trailing edge does not show the same behavior in the FLE that the leading edge does, offering a mitigating explanation for the lack of support in that instance.

**Hypothesis 3**

The third hypothesis stated that in the FTC paradigm, a sufficiently high luminance ratio (high $I_{\text{flashing}}/I_{\text{moving}}$) would induce a flash lead effect, i.e., the moving stimulus would be perceived to disappear short of the perceived flash position, which
would be aligned with the actual disappearance point of the moving stimulus. The literature here is mixed. The postdiction theory (Eagleman & Sejnowski, 2000) argues for veridical perception. Kanai, Sheth, and Shimojo (2004) argue that at a large enough eccentricity, there will be a flash lag (overshoot of the moving stimulus), whereas Roulston, Self, and Zeki (2006), based on a positional averaging mechanism, claim that the moving stimulus will fail to perceptually reach its extinction point. The Roulston et al. position is most consistent with Baldo and Caticha’s model (2005) because the simple instantiation of a leaky-integrate-and-fire model is inherently a mechanism to compute a trailing average; i.e., it is inherently looking backward over the integration period, absent strong feedforward lateral connections not present in his model.

<table>
<thead>
<tr>
<th>Series</th>
<th>Experiment</th>
<th>Description</th>
<th>Statistical Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4-S</td>
<td>FTC- spatial</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum</td>
<td>(F(1,12) = 2.00, p &gt; .05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FlashLum</td>
<td>(F(1,12) = 0.01, p &gt; .05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum x FlashLum</td>
<td>(F(1,12) = 4.58, p &gt; .05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Collapsed FLE</td>
<td>(t(12) = -4.01, p &lt; .001)</td>
</tr>
<tr>
<td>2</td>
<td>4-S</td>
<td>FTC- spatial</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum</td>
<td>(F(1,15) = 0.30, p &gt; .05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FlashLum</td>
<td>(F(1,15) = 0.24, p &gt; .05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum x FlashLum</td>
<td>(F(1,15) = 0.04, p &gt; .05)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*Foveal Approach</td>
<td>(F(1,15) = 15.72, p &lt; .001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>**Foveofugal FLE</td>
<td>(t(15) = -9.403, p &lt; .0001) (1t)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>**Foveopetal FLE</td>
<td>(t(15) = -5.989, p &lt; .0001) (1t)</td>
</tr>
</tbody>
</table>

*Significant at .001  
**Significant at .0001

Table 5. Summary of FTC-Spatial experiments all statistical tests.

In the first series of experiments, there were no main effects or interactions allowing for the collapse of all spatial offset data across all the factor levels (averaged across all eight conditions) per subject. This resulted in a mean flash lead of 0.139° (8.33 minutes) of visual angle \((t(12) = -3.64, p < .01)\). This partially supports hypothesis 3 in
that there was indeed a flash lead, but not one that was dependent on luminance. However, the higher $I_{\text{flashing}}/I_{\text{moving}}$ ratio did produce more flash lead ($0.133^\circ$ vs. $0.113^\circ$) and the interaction F-ratio had a p-value of .054. With an ‘n’ of only 13, this merits further investigation.

In Experiment Series 2 (FTC-S) there was a significant effect of the foveal approach factor ($F(1,15) = 15.72, \ p < .01$). Collapsing the data across all the other factors (luminance levels for both moving and flashed stimuli) yielded a foveopetal value of 9.4 arc-min of visual angle ($t(15) = -5.99, \ p < .0001$) and a foveofugal value of 12.7 arc-min of visual angle ($t(15) = -9.40, \ p < .0001$). This is similar to the result in experiment series 1, except that in this case there was a foveal approach dependence and no hint of an interaction between luminance levels. The interaction between the foveal approach level and the luminance of the flashed stimulus ($F(1,16) = 6.64, \ p = .021$) did not reach our .01 criterion level, but probably warrants further investigation into the nature of the effect of luminance on this particular effect.

Both experimental series of FTC-S resulted in the moving stimulus failing to perceptually reach the actual point of disappearance. This is an important finding, but this phenomenon’s lack of luminance dependence means that the specific hypothesis is not supported. However, that it falls short under this wide a range of luminance ratios is significant and argues strongly for models that inherently compute trailing averages, not postdictive or extrapolative models.

**Hypothesis 4**

Hypothesis 4 stated that in the FTC paradigm, the extinction of the moving object should be affected by the relative luminance of the two stimuli. Specifically, a high
luminance ratio (high $I_{\text{flashing}}/I_{\text{moving}}$) should result in the flash perceptually extinguishing temporally after the moving stimulus does and a low luminance ratio (low $I_{\text{flashing}}/I_{\text{moving}}$) should result in the flash perceptually extinguishing before the moving stimulus does.

Thus, for the second case, in order for the flashed and moving stimuli to be seen disappearing simultaneously, the moving object would need to disappear sooner than the flash. In this case, the results of the two different experimental series were different. In series 1, the flash’s disappearance had to be indexed forward by 62.7 ms ($t(12) = -5.75, p < .0001$), meaning that the moving object was perceived to disappear before it actually did, as predicted by the hypothesis. There was no significant effect (at $p < .01$) of any of the three factors, but both moving luminance and foveal approach neared significance ($p = .019$ and $p = .029$, respectively). When the moving stimulus was brighter, the flash had to be accelerated more, meaning that it was seen to disappear even sooner than when it was dimmer, a somewhat non-intuitive outcome.

<table>
<thead>
<tr>
<th>Series</th>
<th>Experiment</th>
<th>Description</th>
<th>Statistical Result</th>
</tr>
</thead>
</table>
| 1      | 4-T        | **FTC-temporal**  
MoveLum  
FlashLum  
MoveLum x FlashLum  
Foveal Approach | $F(1,12) = 7.36, p < .05$  
$F(1,12) = 1.91, p > .05$  
$F(1,12) = 0.07, p > .05$  
$F(1,12) = 6.19, p < .05$ |
| 2      | 4-T        | **FTC-temporal**  
MoveLum  
FlashLum  
MoveLum x FlashLum  
Foveal Approach | $F(1,15) = 5.05, p < .05$  
$F(1,15) = 6.61, p < .05$  
$F(1,15) = 7.14, p < .05$  
$F(1,15) = 5.89, p < .05$ |

Table 6. Summary of FTC-Temporal experiments all statistical tests.

In Series 2, the stimuli were seen to disappear virtually simultaneously, although individual outcomes ranged from -44 ms to 60 ms. As in Series 1, none of the factors
significantly affected the judgment at $\alpha = .01$, although all three main effects and the interaction between the luminance levels neared significance.

**Hypothesis 5**

Hypothesis 5 stated that in the FIC paradigm, the moving stimulus would perceptually appear some distance downstream of the origination point. The suggested mechanism for this effect in the Baldo and Caticha neural model is independent of the perceived temporal order of appearance and it therefore predicts that only variables that involve spatial judgments would affect this position judgment. Therefore, according to the model, no magnitude of luminance ratio (high $I_{\text{flashing}}/I_{\text{moving}}$) will be able to overcome the spatially induced flash lag effect, as the excitatory cascade of the moving target requires space to reach its perceptual endpoint.

In Series 1, Experiment 4, the spatial offset was significantly dependent on the luminance of the moving stimulus ($F(1,14 = 20.7, p<.001$), noting again that this paradigm failed the homogeneity of variance requirement. The mean offset for the dim level of the moving stimulus collapsed across both of the other factors was 0.0703° ($SE =$

<table>
<thead>
<tr>
<th>Moving Luminance (cd/m²)</th>
<th>Flashing Luminance (cd/m²)</th>
<th>Foveal Approach</th>
<th>Mean(deg) (Positive values = FLE)</th>
<th>SE</th>
<th>One sample t-test (compare to zero)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>242</td>
<td>242</td>
<td>Petal</td>
<td>0.0509</td>
<td>0.0782</td>
<td>0.65</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>242</td>
<td>242</td>
<td>Fugal</td>
<td>-0.0227</td>
<td>0.0514</td>
<td>-0.44</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>242</td>
<td>56</td>
<td>Petal</td>
<td>0.0651</td>
<td>0.0873</td>
<td>0.75</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>*242</td>
<td>56</td>
<td>Fugal</td>
<td>-0.1762</td>
<td>0.0390</td>
<td>-4.52</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>56</td>
<td>242</td>
<td>Petal</td>
<td>0.1640</td>
<td>0.0744</td>
<td>2.21</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>56</td>
<td>242</td>
<td>Fugal</td>
<td>-0.0198</td>
<td>0.0426</td>
<td>-0.47</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>56</td>
<td>56</td>
<td>Petal</td>
<td>0.1901</td>
<td>0.0777</td>
<td>2.45</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>56</td>
<td>56</td>
<td>Fugal</td>
<td>-0.0532</td>
<td>0.0483</td>
<td>-1.10</td>
<td>&gt; .00625</td>
</tr>
</tbody>
</table>

* significant at $\alpha = .00625$

Table 7. Summary of FIC-Spatial FLE levels relative to 0 with Type I error managed using Bonferroni modified significance limits ($\alpha = .00625$).
.0315°) and significantly different from zero (t(14) = 2.22, p < .05). However, and contrary to the hypothesis, the bright moving stimulus level was not significantly different from zero evaluated on the same basis. The safest analysis of the data is to manage the Type 1 error by using a Bonferroni correction and examine each condition result relative to the hypothesis. This would reset the α to .05/8 = .00625.

Table 7 shows the individual condition outcomes and their FLE. This analysis method shows that all but one of the conditions is not significantly different from zero and the one that is different is a flash lead, thus not supporting the hypothesis.

In series 2, Experiment 3, there were significant main effects of the foveal approach factor (F(1,16) = 26.7, p < .0001) and the moving stimulus luminance (F(1,16) = 31.0, p < .0001), as well as a significant interaction between them (F(1,16) = 11.9, p < .01). Collapsing across levels of the flashing stimulus luminance yields FLE values for the 2 x 2 interaction shown in Figure 34.

Specifically testing the smallest FLE value among the four directly tests hypothesis 5. This was the combination of the bright moving stimulus and the foveofugal level of the foveal approach factor. The FLE was 0.11° and the one-tailed t-test showed that this value was significantly different from zero (t(16) = 2.75, p < .01). All of the other FLE values were much higher and also significantly different from zero (Table 8).
Since, as mentioned in the results section, this paradigm failed the homogeneity of variance test, forcing caution in fully accepting the above analysis. Similar to the series 1 treatment, a Bonferroni criterion on direct measures of each condition vs. zero would mitigate that issue. Using 1-tail tests, seven of eight of these specific conditions had significantly positive values (Table 8). The single case that did not neared significance, and that condition was one of the foveofugal conditions, which in many of the cases within this experimental series has been shown to have lower FLE values.

<table>
<thead>
<tr>
<th>Moving Luminance (cd/m²)</th>
<th>Flashing Luminance (cd/m²)</th>
<th>Foveal Approach</th>
<th>Mean(deg) (Positive values = FLE)</th>
<th>SE</th>
<th>One sample t-test (compare to zero)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>*242</td>
<td>242</td>
<td>Petal</td>
<td>0.4179</td>
<td>.0692</td>
<td>6.154</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>*242</td>
<td>242</td>
<td>Fugal</td>
<td>0.1016</td>
<td>.034</td>
<td>3.023</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>*242</td>
<td>48</td>
<td>Petal</td>
<td>0.666</td>
<td>.117</td>
<td>5.406</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>242</td>
<td>48</td>
<td>Fugal</td>
<td>.1260</td>
<td>0.0545</td>
<td>2.072</td>
<td>&gt; .00625</td>
</tr>
<tr>
<td>*48</td>
<td>242</td>
<td>Petal</td>
<td>0.6554</td>
<td>0.0831</td>
<td>8.230</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>*48</td>
<td>242</td>
<td>Fugal</td>
<td>0.3604</td>
<td>0.0427</td>
<td>8.702</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>*48</td>
<td>48</td>
<td>Petal</td>
<td>0.5953</td>
<td>0.0972</td>
<td>6.092</td>
<td>&lt; .00625</td>
</tr>
<tr>
<td>*48</td>
<td>48</td>
<td>Fugal</td>
<td>0.3504</td>
<td>0.0446</td>
<td>7.855</td>
<td>&lt; .00625</td>
</tr>
</tbody>
</table>

Table 8. Summary of Series 2 FIC-Spatial FLE levels relative to 0 with Type I error managed using Bonferroni modified significance limits (α = .00625).

Thus, Experiment Series 2 lends significant support to the hypothesis, unlike Series 1 that did not, and thus this pair of experiments only partially supports the hypothesis. It is certainly plausible that the complexity of the instructions was a contributing factor to this difference in outcomes between Series 1 and Series 2. It is not likely that the trailing-edge judgment in Series 2 was the difference between them, as the trailing edges tend to have less, not more FLE.
Hypothesis 5a

This hypothesis states that in the FIC paradigm the moving stimulus luminance should affect the FLE, whereas the flashing stimulus luminance should not. Specifically, according to the Baldo and Caticha (2005) model, the dim level of moving stimulus (which should serve to reduce the FLE in the CM conditions) should produce a larger FLE than the high luminance condition, because the position of the moving stimulus will be further downstream before the summing function reaches the perceptual threshold.

This hypothesis was unequivocally supported. In both experimental series, there was a significant main effect of moving stimulus luminance (series 1: $F(1,14) = 20.7, p < .0001$; series 2: $F(1,16) = 31, p < .0001$). The flashing-stimulus luminance level produced no significant effects in either experimental series (Table 9).

<table>
<thead>
<tr>
<th>Series</th>
<th>Experiment</th>
<th>Description</th>
<th>Statistical Result</th>
</tr>
</thead>
</table>
| 1      | 3-S        | **FIC-spatial**  
*MoveLum  
FlashLum  
MoveLum x FlashLum | $F(1,14) = 20.7, p < .0001$  
$F(1,14) = 3.14, p > .05$  
$F(1,14) = 1.60, p > .05$ |
| 2      | 3-S        | **FIC-spatial**  
*MoveLum  
FlashLum  
MoveLum x FlashLum | $F(1,16) = 31.0, p < .0001$  
$F(1,16) = 1.59, p > .05$  
$F(1,16) = 8.1, p > .01$ |

*Significant at .0001

Table 9. Summary of luminance level main effects and interactions for both FIC-S experiments (Series 1 and Series 2). Note that the interaction in Series 2 nears significance. The direction of the effect of this interaction is as expected (dim flash = reduction in moving stimulus luminance dependence).

Hypothesis 6

According to this hypothesis, in the FIC condition the combination of a high luminance flashing stimulus and a low luminance moving stimulus ($I_{\text{flash}}/I_{\text{moving}}$) will produce a temporal order judgment favoring the flash compared to the reverse.
(bright moving & dim flashing). Importantly, the combination of a significant FIC-S and TOJ favoring the moving stimulus would provide support for a differential latency-based argument, whereas a significant FIC-S in the absence of a TOJ favoring the moving stimulus argues against DNL as a mechanism in the FIC paradigm. The Baldo and Caticha (2005) model instantiation can make (and they do) a case that the temporal precedence will range from flash preference to moving stimulus preference.

Whereas the flashing stimulus was perceived significantly sooner in both experimental series (73 ms and 61 ms, respectively), there was no support for the luminance dependence of the effect. Although the specific claim of luminance dependence TOJ was not supported, the fact that the flash was perceived before the moving stimulus is noteworthy. Table 10 shows the specific results for the TOJ experiments.

<table>
<thead>
<tr>
<th>Series</th>
<th>Experiment</th>
<th>Description</th>
<th>Statistical Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3-T</td>
<td><strong>FIC-temporal</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum</td>
<td>$F(1,12) = 0.27, p &gt; .05$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FlashLum</td>
<td>$F(1,12) = 0.58, p &gt; .05$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum x FlashLum</td>
<td>$F(1,12) = 1.53, p &gt; .05$</td>
</tr>
<tr>
<td>2</td>
<td>3-T</td>
<td><strong>FIC-temporal</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum</td>
<td>$F(1,17) = 3.02, p &gt; .05$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FlashLum</td>
<td>$F(1,17) = 0.35, p &gt; .05$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveLum x FlashLum</td>
<td>$F(1,17) = 0.13, p &gt; .05$</td>
</tr>
</tbody>
</table>

Table 10. Summary of luminance level main effects and interactions for both FIC-T experiments (Series 1 and Series 2).

**General Discussion**

**Model Analyses**

**Extrapolation**
While this experimental regimen did not specifically target the extrapolation proposal initially put forward by Nijhawan (1994), several outcomes from these experiments address it. The general notion of extrapolation would suggest that past events influence current perception. Three outcomes argue against an extrapolative model. In the FIC (Series 1, Experiment 3-S; Series 2, Experiment 3-S), there was a significant FLE at least in some of the cases. As amply demonstrated in prior work such as Eagleman and Sejnowski (2000) and Whitney, Cavanaugh, and Murakami (2000), an FLE without antecedent action argues strongly that the FLE cannot be solely attributable to extrapolation. Chappell and Hine (2004) showed that prior events do have a moderate impact on FLE magnitude under circumstances where there is a pre-exposure to the moving object prior to its motion onset. They argue that the overall position averaging process takes the initial position into account, arguing against either a postdictive or positional nonavailability argument later made by Eagleman and Sejnowski (2002). This result may be significant in the context of Baldo and Caticha’s (2005) neural model, which would certainly reflect the excitatory accumulation of the leaky integrator nodes mapped to the initial position. The pre-exposure effect was one of diminishing the FLE by up to 30%, not creating it, and hence even this result is not directly supportive of extrapolation, only that a pre-flash event had an impact. Second, one would expect that in the FTC there would be perceptual overshoot of the moving stimulus. As mentioned earlier, much of the prior work using the FTC paradigm reported veridical observations (i.e., no overshoot). The present experiments (Series 1, Experiment 4-S) did not result in veridical position perception, but resulted in a small, but significant undershoot (flash lead). This certainly adds support against the extrapolation model. Third, in the second
series of experiments, the CM paradigm using the trailing edge of the stimulus resulted in no FLE at all (Experiment 2-L). The two possible complementary explanations for this are that the proximity of the stimuli created a flash drag effect that partially or completely offset the flash lag (Eagleman & Sejnowski, 2007), or that the leading and trailing edges have differential FLEs, with the trailing edges producing a smaller FLE (Watanabe et al., 2001). Given that the observed result of no FLE is contrary to the predicted overshoot, there is additional strength to the argument against extrapolation.

**Differential Neural Latency (DNL)**

This theory argues that a moving stimulus initiates either a forward cascade or spreading activation that excites or disinhibits adjacent retinotopic areas in V1, thus giving an already present moving stimulus a *temporal* advantage over a suddenly flashed stimulus. This temporal advantage manifests in a spatial offset, because of the comparative delay in perceiving the flash. The present project investigated the DNL in the three main experimental paradigms used to study the FLE. The CM is not particularly illustrative, because it really cannot differentiate among the competing theories. However, the FIC and FTC both addressed DNL comparatively.

Experiment 3-S of Series 1, the FIC spatial experiment, revealed an FLE dependence on the moving stimulus luminance. There was a main effect of moving luminance \( F(1,14) = 20.69, \ p < .0001 \) and no effect of or interaction with the flashed stimulus luminance. There also was a main effect of the foveal approach factor \( F(1,14) = 8.82, \ p < .01 \) but no interaction with moving stimulus luminance. The dim moving stimulus produced a larger FLE than the brighter one in both levels of foveal approach, although in the foveofugal case, both values actually represented flash lead. This is
completely contrary to the logic of DNL, wherein a brighter moving stimulus should result in either the same or bigger advantage, but not less. Furthermore, the flashed stimulus was perceived prior to the moving stimulus (Experiment 3-T). These two results together argue strongly against DNL as explanatory for the FIC FLE.

In Series 2 Experiment 3-S, the FIC spatial FLE was positive in every case, but again the dimmer moving stimulus produced a larger FLE. Similarly, the flashed stimulus was perceived before the moving stimulus (Experiment 3-T). Again, this combination of results argues against the DNL being explanatory for the FIC FLE. In the FTC paradigm, the DNL again predicts that there should be a temporal advantage for the moving stimulus. The question is how this advantage would manifest in the FTC. Even if the flashed stimulus temporally lags the moving object, the moving object never travels beyond the point of alignment, so an FLE would not be expected. Based on the temporal-only arguments presented in the previous DNL work (e.g., Baldo & Klein, 1995; Patel, Öğmen, Bedell & Sampath, 2000), one would expect veridical spatial alignment, and the arguments for more rapid perception of the moving stimulus do not necessarily make the case that the stimulus perceived first would also extinguish first. This makes it difficult to use the FTC temporal data to argue pro or con for DNL. However, the spatial results from both experimental series (Series 1, Experiment 4-S and Series 2, Experiment 4-S respectively) were 8 and 11 minutes of spatial stimulus undershoot (standard FLE). These results are not consistent with the DNL prediction of veridical perceived spatial alignment.
Neither the FIC nor FTC offered any support for DNL and significant evidence against it, and particularly so in the case of the FIC paradigm.

**Postdiction**

Postdiction, simply, states that the perceptual system resets at the moment of the flash for purposes of determining position. The perceptual system then integrates post-flash position input over the ensuing 80-100ms, resulting in perceiving a displaced position of the moving stimulus. Postdiction predicts the FIC as being the same as CM, because data prior to the flash are discarded. Postdiction predicts veridical positional alignment perception in the FTC, because a spatiotemporal integration of the final position would only include the actual final position. The present results dispute the veracity of this model in both the FIC and the FTC, but subtly so. If one accepts that the Hess effect (Williams, 1980) is active from the moment of motion initiation, one would argue that the brighter the moving stimulus, the farther forward along its trajectory it would be perceived assuming postdiction. This is, again, opposite the current findings. Certainly, nothing in the postdiction model would argue that dimmer moving stimuli would be perceived forward of brighter ones, as predicted by the Baldo and Caticha (2005) model and hypothesized here. Thus in the FIC, the dependence upon the moving stimulus brightness must be accommodated by a successful model, and postdiction in couple with the Hess effect predicts the opposite and is incorrect. Even without the latency reduction of a brighter moving stimulus, postdiction would simply predict no dependence on the moving stimulus luminance, and it would still be unsupported with these results.
In the FTC, we observed that the moving stimulus was extinguished short of its final position (Series 1, Experiment 4-S; Series 2, Experiment 4-S). This observation is not consistent with postdiction, which predicts veridical perception. Both the FIC and FTC outcomes argue against a purely postdictive model.

**Motion Bias**

Postdiction as a model gave way to motion bias (MB), first described by Eagleman (2007). His work targets the DNL model by showing that objects are not displaced in time, but displaced only in space – the perceived position of an object is determined by the vector sum of the influencing motion that happens over the 100 ms subsequent to the triggering event (the flash in the case of the FLE). It is important to note here that this model, like others, is perfectly adequate to explain the CM FLE.

The FIC result shows an FLE dependence on moving stimulus luminance, with dimmer stimuli exhibiting a larger FLE than brighter stimuli. This result is not predicted by the MB model. The FTC result of the moving stimulus being extinguished prior to the actual point of disappearance is also not predicted by the MB model.

The MB model does not address temporal precedence of events, but does argue that an ‘event’ initiates the position determination process that completes in something less than 100 ms. The current study shows a clear advantage for the temporal precedence of the flash in the FIC, by approximately the amount of integration time proposed by Eagleman and Sejnowski (2000, 2007). This argues that the FLE in the FIC could be much less than in the CM, because the integration window largely includes no perception of the moving stimulus. While this does not directly oppose the MB, it certainly offers no support.
The CM results, particularly those of Series 2 Experiment 2-L, do support the contentions made by the MB model. Eagleman and Sejnowski’s (2007) work sets forth a unified explanation for the FLE, the flash drag effect, the Fröhlich effect, and the flash jump illusion. They also explored the relationship between eccentricity of the stimuli and magnitude of the FLE. They show that the closer the proximity of the stimuli to the fixation point and each other, the larger the flash drag effect, which offsets the flash lag. Sufficient flash drag would clearly negate the flash lag. The Series 2, Experiment 2 result of no FLE in the CM is supportive of the notion that flash drag may have offset the flash lag. This is confounded, of course, with the idea proposed by Watanabe et al. (2001) of differential FLE results between leading and trailing edges of the moving stimuli. That work showed a diminution of the FLE when making the judgment based on the trailing edge of the moving object. Perhaps in concert with the trailing edge effect, the effect of proximity as reported by Eagleman and Sejnowski (2007) explains the absence of the FLE in the CM in the present study, and thus is consistent with the MB model.

**Baldo and Caticha Neural Net Model**

The basis for several hypotheses in this study is the neural model proposed by Baldo and Caticha (2005). This section will describe the results in terms of the predictions made by that model and the implications to the model itself.

In the Introduction, this model was presented as a parsimonious but naïve neural network approach to explaining the array of FLE and related phenomena. That section, also introduced the idea that the model may work well qualitatively without having sufficient complexity to be effectively quantitative. In light of the results found here,
clearly there are some important features of the FLE that need to be accommodated in this or any successful FLE model.

First, ‘adjacent channel’ crossover effects tend to minimize the FLE by inducing flash drag. Whereas the present work cannot disentangle the leading-trailing edge versus the potential flash drag in Series 2, Experiment 2-L, which resulted in no observable FLE, other studies have shown that decreasing stimulus eccentricity induces flash drag (Eagleman & Sejnowski, 2007). Previous studies also have shown that the trailing edge experiences less FLE than the leading edge (Watanabe et al., 2001; Chung et al., 2006). Qualitatively, this makes sense inasmuch as any movement across the retina, although highly suppressed (Burr, 1980), produces some elongation smear such that the trailing edge is further back than the leading edge. Any model should represent some blurring, but include suppression mechanisms to minimize it. Hence, the model should be expanded to cover some width (orthogonal to the direction of motion), with connections that would allow activated adjacent motion channels to affect position determination.

In both experimental series, the FIC temporal experiment (Experiments 3-T in both Series) showed a clear temporal perceptual advantage (60 ms to 70 ms) in favor of the flashing stimulus. This advantage makes qualitative sense in that the model argues for some time/distance requirement for the moving stimulus’ signal to reach the output layer, however the model does not make this prediction. It shows, instead, that the output layer reaches the detection threshold at the same time for both the moving and flashing stimuli. The model fails to make this prediction because the architecture does not adequately distinguish between motion and position determination – it has only one type of output. Area MT produces initial responses virtually simultaneously with V1, and
there is clearly a feedback pathway from MT to V1. It is known that MT lesions produce akinetopsia, a condition that makes intermediate position determination degraded or impossible. It is clear that the model must embrace some form of extrastriate motion processing that ultimately is spatiotemporally combined to make a position percept.

A prediction the model does makes, if the parameters are as established to demonstrate the FIC spatial effect, is that in the FTC the moving stimulus will extinguish early – not reaching its actual termination point. The present results support that prediction, although as in the other cases, the model’s prediction is only qualitative. However, the same ‘module’ that creates extrastriate LIF nodes to accommodate the FIC spatial lag, which is inherently a trailing moving averaging mechanism, should produce the expected premature disappearance in the FTC and for the same reason. Critical here as well is that since the position of disappearance is behind the actual position, lateral connections that produce the theorized activation cascade producing the temporal advantage of the moving object cannot be argued to place it perceptually forward of its retinal position.

For the traditional FLE, the model shows that for moving stimuli, the output layer reaches a perceptual endpoint in three time units, whereas the flash takes four time units, showing a temporal precedence favoring the moving stimulus once in motion. This means that the model predicts a spatially driven FLE for the FIC, a spatially driven flash lead for the FTC, and a temporally driven FLE for the CM.

In its current state, the model, with its three layers and symmetric connections (Figure 11), cannot hope to predict all of the findings of this study, let alone the previous body of research. There is not currently a mechanism to accommodate the
foveopetal/foveofugal difference. In order to do that, the model must be asymmetrically weighted with a direction of motion relative to the position of the fovea. Indeed, given that most FLE experiments have stimuli that progress from the periphery on one side of the fovea to the periphery on the other with the flash occurring randomly along the traverse, this would be critical. Furthermore, there are clear structural arguments for this, given that visual receptive fields are narrowing foveopetally and expanding foveofugally. One could also certainly make an adaptation argument that foveopetal motion has a higher threat level than foveofugal motion, so foveal attraction of motion should be favored.

If the model, as Baldo and Caticha (2005) have designed it, has motion inputs that are three position-units wide rather than one, there is an activation and output asymmetry that develops in the activation of the hidden and output layers at steady-state. The result of this is that the leading edge of the output, once it forms, moves at the rate of the leading edge of the input. However, the trailing edge remains stationary until the length of the output reaches the length of the input. This means that the trailing edge is stationary (in this instantiation, at least) for three ‘clock ticks.’ A spatiotemporal averaging mechanism could place significant weight upon this initial position given that it remains stationary for a time, leading possibly to an explanation of the leading-trailing edge differential observed here and in previous work.

**Implications within the body of previous research**

The exploration of the FLE in this project has yielded expected and unexpected results both compared to the proposed hypotheses and outside those considerations. Even though the experimental framework was normative with respect to the many previous
studies, the putative robustness of the FLE must be challenged somewhat. This study utilized comparatively large convenience samples of observers, many of whom were students in either my or my advisor’s undergraduate classes. Several others were graduate students. Most were completely naïve, knowing neither the hypotheses nor theoretical background of the experiments. Three students were affiliated with our laboratory and had some knowledge, and one of the graduate students had participated in a previous experiment and knew the FLE in general. If the effect is demonstrably robust one might expect more variability with lack of motivation (perhaps typical of an undergraduate doing the experiment for extra credit) or expertise (fluctuating criterion), but one would not expect the effect to vary as much as was seen here. Historical FLE levels measured in time units range from 20 ms to 80 ms. In their cross-modal study, Arrighi, Alais, and Burr (2005) measured the visual-visual FLE in the 20 ms range. Whitney et al. (2000) measured it at 45 ms in a direction-change paradigm, and Purushothaman, Patel, Bedell, and Öğmen measured it as high as 70 ms in cases where the moving stimulus was comparatively detectable (bright). In the CM condition in Series 2 (Experiment 2-L), the range was from 90 ms of FLE to 74 ms of flash lead. With more observers than typical and more naïve than typical, the FLE levels reported here are not surprising. The flash-lead phenomenon has been discussed elsewhere here, but appears to be driven by proximity, trailing edge observations, and the above observer factors.

In 50 randomly selected experimental studies relating to FLE phenomena reviewed for this dissertation, the number of participants ranged from 1 to 39 and averaged 7.44. However, the median and mode were 5 and 4, respectively. Of the 139
experiments represented in these studies, 82 included the PI(s). Several included only the PI and a few close associates who could be regarded as comparative experts in making psychophysical judgments. Kreegipuu and Allik (2003) observed in their review of work done prior to theirs that few authors reported on the significant individual differences found in the studies, although they were clearly present. Significant individual differences coupled with a significant fraction of low-n experiments, clearly adds to the variability of reported outcomes within this literature. Furthermore, in most of the low-n experiments, the non-PI observers were trained observers of psychophysical phenomena, whereas the few cases of comparatively high-n studies had untrained observers naïve to the experimental hypothesis.

One qualitative observation driven by numerous anecdotes was that these judgments were quite difficult to make, and that the desire to pursue the moving stimulus was difficult to suppress. The data bear this out to some extent, although in the second series the eye-tracker observations indicated that participants were indeed able to hold their gaze fixed. A second related qualitative observation made was not attributable to judgment expertise. It was simply the level of difficulty encountered training the participants to understand and follow the instructions. Those potential participants unable to perform the first FLE task were dismissed. However, other participants had to repeat some of the experiments because they juxtaposed the 2-AFC response mapping (pressing the ‘before’ key for an ‘after’ judgment and vice versa). The quantitative observation vis-à-vis the judgment difficulty came in the form of the collected data. The majority of observers did not have 100% of their data unencumbered. Many individual staircases did not conform to the expectation that observers would work their way to their
point of subjective equivalence and then remain stable at that point. Whether this was due to the inherent difficulty in making the judgment, some amount of gaze drift, button press errors, or criterion shifting is impossible to determine, although the first three of these were anecdotally reported.

The aforementioned difficulties in the data collection had three significant impacts. First, it resulted in this researcher to essential repeat the entire experiment using modified stimuli and a simplified procedure. Second, it resulted in the development of a procedure to ‘clean’ the data in an appropriate way. This data cleansing involved the replacement of individual suspect data with data that were, in the end, the condition average modified by the participant’s average z-score bias from the means of the conditions in which the participant had apparently reliable observations (see the Data Analysis section). However, before this procedure was settled on, the entirety of the data was analyzed unmodified and modified by two other procedures. None of these made any material difference as to the conclusions reported here.

The third change that resulted from the data collection issues was the decision to use the more conservative alpha of 0.01 in lieu of the more traditional 0.05. It was determined that using 0.01 as the criterion was justified for two primary reasons. First, it is true that most psychophysical experiments are conducted with well-trained observers who produce data with less variability. Second, although less than 10% of the data was replaced and the replacement method did not broadly affect the ANOVA outcomes to a great extent, the replacement method did affect individual contrasts enough to move them in or out of a 0.05 rejection region. It was, therefore, prudent to suppress possibly spurious significant results by tightening the criterion level. This had the positive side
effect of eliminating several interactions that were not the focus of this study, but may warrant future study.

The investigative question of whether a relationship might be found between the FLE and reaction time was not answered satisfactorily here. Although no statistically significant relationship was found, some additional manipulations of the available data found relationships approaching significance. As previously discussed, there are issues with using RT as a direct measure of neural transmission and cortical processing speed. This factor taken together with the aforementioned data issues suggest that this part of the study might be worth repeating with a more straightforward FLE paradigm that did not include numerous variables meant to elucidate other model components. Instead, the study should be designed to drive precision in a single representative FLE measure, and with participants who are sufficiently trained to ensure reliable measures.

**Limitations**

There are numerous limitations in this experiment. Typically, experiments of this type are undertaken by comparatively expert observers that, whether or not naïve to the hypotheses, are excellent at producing reliable staircases. In order to limit the total amount of time in which the participant was involved to an hour or less, the choice was made to utilize that time for a series of repeated measures experiments. Ordinarily, each data point (in this case an observation within a condition) would have many (30 or more) repetitions to increase precision. To effect the number of conditions, this would have necessitated many hours of testing, fewer conditions, or a between-subjects design. With an objective of having all these conditions and only a finite pool of participants, the second and third options were not viable. Our experience with typical participants not
affiliated with the lab suggests that keeping them for longer than an hour or so begins to affect performance due to at least motivation and fatigue factors. Given the outcome of this set of experiments, several of the conditions could be eliminated and replaced with replications.

A second limitation was in the software. The presumption is that stable staircase endpoints will be achieved with 10 or 12 reversals, recording the final six for the observation. This is intended to create a built-in improvement in the reliability of the observation. However, it is clear from the results that the data were not reliable in many cases. This software had no available logic to test the stability of the last six reversals, whereas more programmable software (e.g., MatLab®) would have been able to easily test this (although time considerations in learning to generate and control experimental stimuli prevented its use here). Had this been available, the endpoint could have been a ‘last six’ reversal pattern that met statistical criteria for use.

A solution to either of the above two problems would have largely prevented the third limitation, which was the amount of required data ‘cleansing.’ While every effort was made to ensure that no type I errors were made due to data artifacts, any time data are replaced there is some risk that the conclusions become suspect, increasingly so with more replacement. In order to mitigate the artifact concern, a more conservative criterion ($\alpha = .01$) was utilized for the statistical analyses. This resulted in several effects being classified as ‘approaching significance,’ when ordinarily these might have been simply accepted as significant. This accommodation increased the risk of a Type II error.

In terms of model generalization, the FLE paradigms employed here were comparatively narrow – horizontal linear motion of high aspect-ratio rectangles.
Previous FLE experiments have been conducted with spinning bars or using apparent motion generated by progressively flashing but segregated bars. If there were to be a universal model explanation, these paradigms also would have to be incorporated.

Related to the first limitation, whereas the FLE may be qualitatively robust under many conditions, many participants anecdotally reported significant difficulty making these judgments, often borne out in their data. One of the recurring themes in examining the data of previous studies is the often significant individual differences observed – which is ‘supportive’ of the often high data variability seen here. Compared to trained observers, one would expect more variability with untrained (and inherently less motivated) observers. One would certainly expect Type II errors to ensue from increases in variability.

A specific methodological issue with Series 1 requires discussion here. Whereas the second experimental series used ‘mapped’ button presses that had left-right meaning, the first series could not, owing to the fact that the motion was bidirectional in an effort to control for any possible motion after effect (MAE) impact. Therefore the button presses were not intuitive, and undoubtedly led (supported by anecdotal post-trial comments) to button-press errors, adding noise to an already difficult judgment.

Palix, Ibanez, and Leonards (2002) showed significant left-right hemifield differences in visual search tasks. Burnham, Rozell, Kasper, Bianco, and Delliturri (2011) noted significant differences in the lateral hemifields in an attention capture task. Finally, along this line, Rebai, Barnard, Lannou, and Jouen (1998) showed lateral asymmetries in spatial frequency response. If any of these or the many other studies on lateral hemifield effects are relevant to the FLE, it would lead to difficulty interpreting a
mixed hemifield experiment. It is certainly reasonable to consider the attention component of the FLE in the context of the Burnham et al. work. To overcome the mapping problem in the second series and simplify the judgments, the MAE and lateral-hemifield bias risks were knowingly taken by running all the experiments left to right. If there were a relevant lateral hemifield effect, it would confound the interpretation of Experiment Series 2, because the foveofugal condition was always in the right hemifield and the foveopetal condition was in the left hemifield. This would be easily overcome by running half of the observers in the opposite direction.

**Future Studies**

Several future studies are suggested from the present study. In order to further refine the Baldo and Caticha (2005) model, the relationship between foveal approach and eccentricity needs to be examined. This study did not address the effect of axial (along the direction of motion) eccentricity on the magnitude of the FLE. Since spatial uncertainty increases with eccentricity, this would have to be accommodated in a comprehensive FLE model. Additionally, and owing to the specific outcome of no FLE observed in Experiment 2 of Series 2 (CM), the orthogonal eccentricity (axis perpendicular to the direction of motion – i.e., separation) vs. FLE must be examined in order to elucidate the number of ‘adjacent channels’ that must be incorporated in a model. The ‘confound’ of interpreting the lack of an FLE in Series 2 Experiment 2 was the proximity of the stimuli and the trailing edge-leading edge effect. A series of experiments that examines the impact that stimulus width has on FLE is necessary to further deconvolute that result.
The Baldo and Caticha (2005) model strongly suggests, supported by the present results, that the FIC and FTC effects are spatially driven, whereas the CM FLE remains open to debate. This argues for a carefully designed study to examine the prospect of a regime change from spatial to temporal drivers and back. By varying the position of the FLE measurement along the path, one should be able to measure at what position and time the prospective temporal advantage of the moving stimulus overcomes the “Fröhlich-like” spatial FLE with concurrent temporal advantage to the flashing stimulus.

If the lateral hemifield effect mentioned in the Limitations section is repeatable and robust, the model also must accommodate that. This means that a series of experiments, ideally in a repeated measures design, need to be undertaken to quantify it and describe under what conditions it might present. For rotating stimuli, the effect of clockwise vs. counterclockwise would be studied, measuring lateral hemifield effects on instantaneous vertical motion (9 and 3 o’clock positions on a rotating stimulus would be vertical at those points).

In order to clarify the possible impact that individual neural transmission speeds have on the FLE, two protocol changes are suggested. First, a noninvasive method of cortical response rates could be made (as opposed to button press rates) and regressed against an FLE protocol that was focused on precision as opposed to varying conditions to examine effects. One might look at FIC or CM separately in an effort to elucidate the transition between a spatially driven effect (FIC) versus a possibly temporally driven effect (CM). It would be an exciting result to discover that the FIC was uncorrelated with RT, whereas the CM was.
In terms of methodology, it is clear that two improvements (relative to the protocol employed here) should be made to overcome the difficulty in making these judgments. First, there must be a means (probably in the software) to ensure criterion stability. The presumption in interpreting a staircase is that by the time six reversals have been made, they are indeed oscillating about a stable criterion. Clearly, that was not always the case in the present work. Second, it seems prudent when using untrained observers to ensure that they reach criterion stability on some basis. This way, if there are significant changes in criterion based on familiarization or initial learning effects, they are not represented in the data.

**Original Findings / Contributions to the Literature**

The single most important finding here is that the mechanism that generates the FIC FLE and the CM FLE must be different and that the FIC FLE has a component that is not temporally driven. This means that even if the FLE is driven by DNL in the CM, it is unequivocally not driven by DNL in the FIC. The evidence for this is that the flash is seen first by tens of milliseconds and yet spatially lags behind. The implications of this are that any comprehensive model must accommodate this finding. Further, it must also be true that if differential latencies are involved in the CM FLE, there must be a transition phase whereupon the spatially driven FIC regime gives way to a temporally driven CM regime. The Baldo and Caticha (2005) model provides a beginning for this modeling.

The second contribution is that in the FTC, the moving stimulus does not, in fact, perceptually reach the actual disappearance point. This adds significant support for trailing-temporal integration models and significantly impeaches both the original extrapolation theory and the postdiction models.
The third contribution is about the Baldo and Caticha model itself. Whereas their model can provide a beginning point and models plausible neural mechanisms, it is inadequate in its current form to fully capture the range of observed phenomena associated with the FLE. The present work, therefore, has provided significant support to the notion of this model while not quantitatively supporting its original instantiation.

Finally, the FLE often is introduced in the literature as an observational fait accompli. This is one of those situations where notions are promulgated until they reach ‘everybody accepts this’ status without question. As mentioned earlier, many studies were comparatively small-n designs and used PIs and/or trained observers as a significant portion of the participant pool. They generally did not emphasize the individual differences present in their own studies. The present study used a preponderance of untrained and naïve observers. The data were noisy, provided difficulties in analysis, and had large within-variance, thus reducing power. This data-noise indicates that the statements about the robustness of the FLE would be more accurate if accompanied by statements about significant individual differences. The most dramatic case of this observation came with the trailing-edge CM FLE (Series 2, Experiment 2, Figure 31). The results histogram was approximately normal and showed a range exceeding 220 ms of FLE (M =.008 ms, SD =.043 ms), therefore there was nothing obviously erroneous or biased in the data. Still, the wide dispersion begs for explanation.

The two most ‘expert’ observers in the CM FLE experiment were very close to each other (0.31 SD) and both had individual mean scores greater than 1.25 SD from the grand mean. Many of the previous studies used expert observers with a few naïve
observers. This mixture may not generally be reflective of the population or it portends that the trained population is meaningfully different that the naïve population.

This study attempted to associate reaction time with FLE levels, and was generally unsuccessful, although a small effect might emerge with sufficient power. However, macaque studies do, however, show time-to-V1 variability. Spatial uncertainty can contribute to dispersion, and no attempt was made to measure or utilize visual acuity. Studies at Wright Patterson Air Force Base (Winterbottom, unpublished) show performance differences in tasks between 20/20 and 20/13 (the mean of Air Force pilots). To the extent that significant individual differences make modeling difficult, the present series of experiments argues that some individual characteristic data might be useful in normalizing results, making further studies less susceptible to those differences, particularly in those cases where small-n designs are used.
References


http://www.youtube.com/watch?v=01LMFFpAWYM


