UNIVERSITY OF CALIFORNIA
Los Angeles

A physical model for peripheral semantic vision and physics education improvements for life scientists

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

by

Elizabeth Anne Falcone Mills

2020

ABSTRACT OF THE DISSERTATION

A physical model for peripheral semantic vision and physics education improvements for life scientists

by

Elizabeth Anne Falcone Mills
Doctor of Philosophy in Physics
University of California, Los Angeles, 2020
Professor Katsushi Arisaka, Co-chair
Professor Ian S. McLean, Co-chair

We propose an attention-based theory for how humans extract semantic information from objects located in our peripheral visual field. We build upon the scale invariance for extraction of semantic information from objects in center gaze. Our theory for peripheral vision hypothesizes that a vision attention vector runs parallel to the brain's main visual pathway. Information from this vision attention vector is able to combine with our brain's representation of our visual field, such that a peripheral target is able to be remapped and represented at center, in a downstream stage of the brain's visual processing. We connect our theory to previous observations of peripheral vision impairments and documented cases of specific types of letter confusions. We simulate these past findings by modeling peripheral vision object identification failures as an off-target vision attention vector. Our own crowding experiments show support for an active, attention-based mechanism for extraction of peripheral semantic information. We show that a fully crowded visual environment degrades peripheral vision abilities by over twice that of a locally peripherally crowded visual environment ($P = 2.02 \times 10^{-10}$). Additionally, we find instances where a letter on the outside of a peripheral cluster yields a smaller threshold letter height, as compared to a letter on the inside of that same peripheral cluster ($P = 1.20 \times 10^{-2}$). Such combination of simulation and

experiment results offer support for our vision attention vector theory, which is, insofar as we are aware, the first comprehensive theory for how humans can extract a single semantic representation for objects anywhere in the visual field.

Additionally, we review our physics for life sciences (IPLS) laboratory revisions that have positively impacted over 4,850 undergraduate students at UCLA. To achieve learning outcomes of improved critical thinking and problem-solving persistence, we used a combination of "flipped" pre-laboratory assignments, inquiry-based in-lab activities, and peer-based learning with undergraduate learning assistants. As a result of our revisions, an increased number of students reports pursuing their own scientific questions during physics experiments. On average, students show a pre/post quarter attitude shift of 0.50 Likert Levels ($P = 4.1 \times 10^{-12}$), as shown by E-CLASS assessment analysis. We additionally show that, after a second round of revisions, a decreased number of students reports immediately asking an expert like the instructor for help when facing a challenge during an experiment. (pre/post quarter attitude shift of -0.23 Likert Levels ($P = 1.0 \times 10^{-4}$)). Therefore, our evidence-based revisions of undergraduate physics labs show an increased development of important physics skills in our next generation of healthcare professionals. Our revisions may serve as an example to support other institutions in nation-wide efforts to optimize undergraduate physics education.

The dissertation of Elizabeth Anne Falcone Mills is approved.

Aaron Paul Blaisdell

Sandra Kan Loo

Agatha Lenartowicz

Joshua Fred Samani

Katsushi Arisaka, Committee Co-chair

Ian S. McLean, Committee Co-chair

University of California, Los Angeles

2020

To H. H. Jagadguru Sai Maa Lakshmi Devi Mishra

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGMENTS

Thank you Katsushi Arisaka, Agatha Lenartowicz, Joshua Samani, and Shanna Shaked for your mentorship during my graduate school experience.

Katsushi, thank you for sharing both your teaching and research aspirations with me, for welcoming me into your laboratory, and believing in my ability to succeed as a researcher. I am grateful for your example as a creative, hard-working, disciplined, and relentless researcher. Your example and support has trained me to build my own resilience, focus, and persistence in achieving both teaching and research goals. I am grateful for your direct and clear communication, that has helped me build upon my strengths and improve upon my weaknesses. I am honored to be part of your scientific progress to characterize unifying neural mechanisms for how humans think and behave. I look forward to future collaborations.

Agatha, thank you for welcoming me into your class, and extending this welcome into your research group. I am grateful for your example as a multi-faceted researcher who is using academic and clinical research to make a positive difference in the world. I appreciate all the communication and organizational skills that I have learned from you, and I also look forward to our future collaborations together.

Josh, thank you for your friendship and mentorship, as a teacher and researcher. When I have fears about achieving my goals, I reflect on our conversations and can activate a growth mindset because of all the times you shared your struggles and believed in my abilities! I am grateful for your support in grant writing, curriculum development, and teaching. I look forward to our future collaborations on teaching physics.

Shanna, your impact on my graduate school experience cannot be quantified by words. Thank you for being my mentor in my very first quarter of teaching at UCLA, and for supporting me consistently, every quarter onwards. You believed in me, even during the times that I did not believe in myself. Your own example as a human being is the single greatest factor that supported me to persist in graduate school, and create my own PhD project that I am proud to continue as a professional physicist throughout my life.

Thank you Aaron Blaisdell, Sandra Loo, and Ian McLean, for your academic and personal support during my time in graduate school. I am grateful for academic and organizational expertise that each of you offer in your own disciplines. I have benefitted tremendously from our conversations and your example.

Thank you Jone Bacinskaite, Javier Carmona, Sonia Chung, Christopher Dao, Anna De Schutter, Saba Doustmohammadi, Chandan Kittur, Steve Mendoza, Tomoyo Namigato, Ikaasa Suri, Patrick Wilson, and Justin Yi for all your research contributions in the Arisaka Lab and your friendship to support me, personally during my PhD. Together, we have transformed the Arisaka Lab from studying *C. elegans* as our experimental biological model, to studying humans as our model organism. I am grateful for all your creative experimental ideas, un-ending questions to better your understanding of our research endeavors, and your overall amazing attitude and optimism about being able to achieve meaningful results and gain insights in this messy field of human research.

Thank you Mihai Bibireata, Vishal Dobaria, Kishan Ghadiya, Anwar Zane Harb, Amanda Nguyen, Meghna Patel, Sofia Perez Guzman, Natalie Rotstein, Sunrae Taloma, and Salwa Zahid for all your contribution the UCLA IPLS Laboratories revisions, through your service in the UCLA LA Program, and going above and beyond your undergraduate learning assistant responsibilities repeatedly, for the sake of improved student learning, and the betterment of our UCLA physics laboratory curriculum. You have also taught me so much, in how to mentor, collaborate, and listen, and I am forever grateful for all our time together. I wish you all the best in your journey onwards as professionals in your careers; the world is better place because of your hard work, and your genuine care for education and humanity. I had a really enjoyable experience working with you all, and we accomplished a lot!

Thank you Joshua Adams, Raymond Chang, Chandan Kittur, Chia-Hsi Jessica Lin, Philip Lu, Steve Mendoza, Travis Myers, and Paul Pinchuk for your extensive support for the development and implementation of UCLA's revised IPLS laboratories. I thank you for your trust, your collaboration, honest feedback, and insightful work above and beyond

your TA appointments to make these Physics 5 Series labs a concrete reality. You all have sacrificed time that could have otherwise been put to your PhD research, to support our cause for better undergraduate physics education. I am forever grateful. I wish you all the best in your careers as professional physicists. See you around, and keep in touch!

Thank you Eric D'Hoker, Michael Gutperle, Alexander Levine, John Miao, Seth Putterman, and Shenshen Wang for my graduate physics education. I am grateful for your mentorship, understanding, and example. Every time that I teach physics, I personally reflect on the high level examples we explored together, and, because of your foundational support, I am able to deepen my own conceptual and mathematical understanding.

Thank you Dolores Bozovic, Justin Faber, Albert Kao, Chia-Hsi Jessica Lin, Sebaastian Meenderink, Patricia Yuki Quinones, and Yuttana Roonthsumskul, and Janaki Sheth for being my laboratory group mates for a large part of my physics graduate school experience. I personally have grown, as a scientist and a human, through our time together. It is of direct result of my accomplishments and failures during this time that I have been able to realize my own life's passion as an educator and researcher. Your resources in time, energy and funding that you all graciously dedicated to me during this time personally supported me in my scientific training, such that I was able to achieve this thesis work in the Arisaka Lab.

Thank you Zhara Aghajan, Stuart Brown, Peter Collings, Catherine Crouch, Katherine Hayes, Rachel Kennison, Marc Levis-Fitzgerald, Jeffrey Maloy, Nicole Mancevice, Liz Roth-Johnson, Arlene Russel, Erin Sanders O'Leary, Herwig Shoen, Casey Shapiro, Erin Spark, Kei Takahashi, and Liliya Yatsunyk for your example as hardworking and motivated researchers. I am grateful for all the information and insights that you have taught to me, and I have learned so much from you.

Thank you Aijah Bowens, Leticia Cabeza, Christina Ferreira, Jay Hauser, Stephanie Krilov, Ronald Ma, Jason Mesa, Rick Morishita, Ernesto Najar, Frank Neverez, Dorothy Page, Francoise Queval, David Salzberg, Patrice Tonnis, and Jazmine Vega, for supporting my wellbeing, as well as my many projects, in the UCLA Physics and Astronomy Depart-

ment. I am grateful for your time, energy, and care.

Thank you Polina Abatcheva, Zhara Alavi, Daphne Chen, Lizzy Comuzzi, Joel Diaz, Katie Dixie, Alex Latshaw, Jared Lodico, Vasha Narace, Liya Oster, Nayana Rajapakse, Stephanie See, Janaki Sheth, Holly Truong, and Agnieszka Wergieluk. Your friendship during my time in graduate school has supported me beyond what words can describe. I am grateful for all the ways that you cared for my wellbeing and our enjoyable experiences together, and I have learned so much from you.

Thank you Madeline Falcone, for your relentless efforts to educate yourself, and, against all odds, to educate me. Because you shattered your glass ceiling, I could lasso the moon. Now I'm heading onwards to the stars.

Thank you Tom Neiser. The last seven years have been the most rewarding and growth-filled years of my life, in large part because of your constant friendship and unconditional love; I am grateful for our time together at UCLA. As I cross the threshold into my career as a professional physicist, I say, once again, "I do." I do believe that we can create lasting change to better our world.

I would like to acknowledge the many additional individuals who have contributed to my overall life experience and personal development, to bring me to this point in my life. Thank you to all of my friends, mentors, colleagues, and family, past and present. Thank you for your authentic support, through my successes and failures, the praise and constructive criticism. I am grateful for the good, the bad, and the ugly, because it is through such unadulterated experience that I have been able to choose my life's path for myself and learn to stand tall in my own skin. Om Jai Jai Sai Maa. Namaste.

This work is supported by the UCLA Department of Physics and Astronomy, UCLA Division of Physical Sciences, UCLA Division of Life Sciences, and UCLA Center for Advancement of Teaching (CAT), formerly known as the UCLA Office of Instructional Development (OID), under two UCLA IIP Grants: *Physics Optimized for Life Science Majors: New Course Development of Physics 5 ABC and Labs*, AY17-18, and *Data-driven, Systematic, and Sustainable Transformation of Physics for Life Scientists*, AY18-19. All experimental

study design, assessment, and analysis was in accordance with the University of California, Los Angeles Institutional Review Board (IRB #19-000751, *Visual Acuity and Microsaccades* and IRB #19-000578, *Assessing Physics for Life Sciences*).

VITA

2007–2011	**BA, High Honors** (Chemical Physics, Astronomy minor), Swarthmore College, Swarthmore, PA
2011–2013	Laboratory Technician, Dept. Physics & Astronomy, UCSD
2013–2015	Graduate Student Researcher, Dept. Physics & Astronomy, UCLA
2013–2015	**Master of Science** (Physics), UCLA, Los Angeles, CA
2015–2017	Women in Physics and Astronomy Group and Conference Chair, Dept. Physics & Astronomy, UCLA
2015–2018	**PhD, Candidate** (Physics), UCLA, Los Angeles, CA
2015–2020	Graduate Teaching Assistant, Dept. Physics & Astronomy, UCLA
2016–2017	Outstanding Teaching Award, Dept. Physics & Astronomy, UCLA
2016–2018	Curriculum Developer, Dept. Physics & Astronomy, UCLA
2017–2018	Learning Assistant Instructor, Dept. Physics & Astronomy, UCLA
2016-2029	CIRTL Scholar and STAR Fellow, Center for Integration of Research, Teaching & Learning, UCLA Chapter, Los Angeles, CA
2018–2019	Charles E. and Sue K. Young Award Fellow, UCLA
2019–2020	TA Training Specialist, Center for Advancement of Teaching, UCLA

PUBLICATIONS AND PRESENTATIONS

I. Suri, P. Wilson, S. Doustmohammadi, A. De Schutter, N. O'Connell, T. Chunwatanapong, S. Varadharajulu, J. Tan, R. Govin, S. Dureja, A. Lai, K. Arisaka, and **E. Mills**, "Perceiving the Periphery: Investigating how we extract semantic information across our visual field," in preparation (2020).

K. Arisaka, J. Hauser, **E. Mills**, G. Trammel, S. Shaked, A. Blaisdell, "Development of Flipped/Asynchronous Online Physics Labs," UCLA IIP Grant Award, June 2020.

K. Arisaka, J. Hauser, G. Trammel, J. Samani, S. Shaked, F. Queval, C. Kittur, **E. Mills**, "Development of Hands-on Physics Laboratory for Scientists and Engineers," UCLA IIP Grant Award #19-04, June 2019.

E. Mills, N. Rotstein, C. Dao, S. Mendoza, C. Kittur and K. Arisaka, "Physiological Measurement, Sense-Making and Analysis in University IPLS Laboratories", *Society for Neuroscience Annual Meeting, San Diego, CA*, Nov. 2018, *AAPT Winter Meeting, Houston, TX*, Jan. 2019, *SABER West, Irvine, CA*, Jan. 2019.

E. Mills, S. Shaked, J. Samani, K. Arisaka, "Mixed-Methods Assessments of Introductory Physics for Life Sciences," *CEILS Journal Club*, Nov. 2018.

I. McLean, K. Arisaka, J. Samani, G. Trammel, **E. Mills**, and S. Shaked, "Data-driven, Systematic, and Sustainable Transformation of Physics for Life Scientists," UCLA IIP Grant Award #17-13-01, June 2018.

E. Mills, A. Latshaw, R. Ravirasad, and J. Chieu, "2017 Conferences for Undergraduate Women in Physics," *Am. Phys. Soc.* CUWiP Conferences Host Recipient, Nov. 2015.

E. Mills and D. Bozovic, "Probing Hair Cell Mechanics with Magnetic Nanoparticles: Suppression and Recovery of Limit Cycle Oscillations," *Biophysical Society Meeting, Baltimore, MD*, Feb. 2015.

E. Mills, M. Regan, V. Stanic, and P. Collings, "Large Assembly Formation via a Two-Step Process in a Chromonic Liquid Crystal", *Jour. Phys. Chem. B*, 116 **45** (2012).

E. Mills and P. Collings, "Molecular Assembly and Liquid Crystal Properties of a Near-IR Absorbing Dye ", *American Physical Society National Meeting, Boston, MA*, March 2012.

CHAPTER 1

Introduction

The purpose of this dissertation is to highlight my design, implementation, and analysis of novel neurophysics experiments and the physics education curriculum at the UCLA physics and astronomy department. In the field of psychology and neuroscience it is still an open question how humans extract the semantic meaning from objects, in an invariant way that is independent of object size, orientation, or position in space. As our human brains are still outperforming Artificial Intelligence (AI) technology for object recognition and semantic invariance, it is useful to explore how our brain is able to unconsciously process information and match it to previous experience. Using the rotational and dilation invariance of the logarithmic polar coordinate remapping intrinsic to our primary visual cortex, we show that our brain can easily match objects of different sizes and orientation, when our eyes are already looking at the object. To explain peripheral vision, we propose a novel mechanism for vision that uses all three pathways for visual processing that are currently known to exist in the human brain. Current models emphasize a bottom-up, passive mechanism for visual processing. This passive perspective uses known peripheral vision limitations resulting from eccentricity-dependent pixel size within the retina, resulting in reduced spatial resolution as a function of object peripheral location. In addition to passive, bottom-up visual constrains, our model includes an active, attention-based component, that describes how our brain extracts semantic information in a scale invariant way, for objects located anywhere in the visual field. We combine simulations of past literature findings with novel experiments to test our model for human semantic vision.

In the second part of this thesis, I present Introductory Physics for Life Sciences (IPLS) Laboratory revisions, which have improved the physics attitudes of over 4850 undergraduate students over the last three years. In 2017, the UCLA Physics and Astronomy Department took the initiative to completely rebuild its lecture and laboratory curriculum to better support the needs of its life sciences students. Over the last 30 years, physics education research across the country has shown that life science students are able to gain important physics conceptual and critical thinking skills that serve them in their future careers (Smith et al., 2018). However, such successes in student learning gains have been achieved when the physics curriculum is adapted to better support critical thinking and skills for persistence learning in non-major students (Crouch et al., 2018). In our revisions, we created "flipped" classroom pre-laboratory assignments, inquiry-based laboratory activities, and a laboratory learning community of faculty, staff, graduate teaching assistants (TAs), and undergraduate learning assistants (LAs) to support student learning. Using validated assessment tools, we show that our revisions improve student attitudes about their critical thinking and persistence skills during their physics laboratory experience. This shows that our revisions have achieved their objectives, and our methods may guide future laboratory curriculum revisions.

Part 1

Perceiving the Periphery: Investigating how we extract semantic information across our visual field

CHAPTER 2

Background & Motivation

2.1 Human vision is extraordinary

Human vision is an extraordinary technology that combines sensation of present visual information with perception of meaning, relative to past memory and future planning. It is easy to take our own human vision for granted, as we develop such ability to sense and perceive from a young age. Our brain is unconsciously trained to recognize, extract, and remember particular features about our visual environment, such that we are prepared to assign meaning and make connections in response to future visual input at a later time (Baars and Gage, 2010; Hebb, 1949).

Our brain has complex and diverse mechanisms for processing visual information from the environment, and assigning distinct meaning to specific aspects of the vision content. While the anatomy of the vision system in the eye to brain connection is well established, the physiology of how our brain makes sense of the vision input, in context to past experience and future objectives, is still an open question. We do know that the organization of visual information in our visual field is very different from the organization of visual information as stored in our brain, and there has already been advancements in AI technology that have applied aspects of human vision anatomy to achieve better object recognition capabilities in agriculture, self-driving cars, and security systems (Beyeler et al., 2019; Dowling, 2005; Qi et al., 2006; Zhao et al., 2018).

The physiology, or real-time communication between cells in the eye and cells in different parts of the brain is still an open question because of the diverse spatial and time scales that information is detected, measured, and relayed within the brain. The human brain is able to uptake information from a two-dimensional visual field with many independent pixels (our retinal photo-receptors), and produce continuous, real-time, unified, conscious perception, with time-lag only on the order of 50ms. While we know that our brain achieves this with many parallel processing streams, scientists have not adequately explained how these parallel processing streams communicate on the same clock to recombine information assigned to the same original timestamp of our real-world visual sensation (Baars and Gage, 2010; Hebb, 1949).

Such complexity of visual perception calls forward two fundamental research questions, which must be understood and answered, in order for us to explain human vision. Firstly, given a single piece of visual information, how do we recognize or "match" this visual input, independent of size or orientation in our visual field? When you look at Figure 2.1, your brain will process the same semantic meaning of a rose, independent of size or orientation. Much of this processing happens subconsciously, whereby we are not aware that the rose has rotated 15 degrees from the top left panel to the top right panel. In the case where an image has dilated, or become magnified in size, our brain attributes the size change to spatial information, while preserving the same semantic information. For example, when the rose becomes larger, it may consciously seem that one has moved closer to the rose, but that it is the same rose.

The second question that must be answered pertains to how we are able to semantically extract information from everywhere in our visual field, as in the case of an extended object, or an object that is not centered in our gaze. When you look at Figure 2.1, and focus your gaze to the yellow center of the large bottom rose, you may still recognize the two smaller roses in your upper visual field. They may be a bit blurry, but there are probably still color gradients, and general shapes or forms that you are able to extract. While keeping your gaze fixated at the yellow center of the large bottom rose, perhaps you can even shift your attention back and forth between the two smaller roses, and compare how they are similar in semantic quality, with rotated outer border geometry. Our ability to extract semantic information via our covert (not-center-gaze) attention is an incredible ability whose mechanisms remain to be fully explained.

The remaining background on our human vision summarizes anatomical organization of how the human brain maps the visual field into brain tissue coordinate-space, motivation for why such anatomical organization explains central vision (covert attention), and justification for why such current knowledge does not explain how humans are able to extract semantic meaning from information in the peripheral visual field. Motivation is established for why peripheral vision is so important, as well as a brief literature review outlining viewing conditions where peripheral visions is maintained versus where it breaks down. Such review is able to motivate our hypothesis for our theoretical model of covert attention and support the specific designs for our own visual acuity experiments.

For nearly one hundred years, scientists have been trying to crack the code on how we are able to recognize and extract semantic meaning from an object, independent of background, size, orientation, or even color. execute optimal actions to use this visual information to achieve a desired outcome. While our society has made great strides in supporting individuals with visual impairments, these individuals make the minority, and must be supported by others who are able to visually engage with the world, to prepare information in a way that can be received by those who cannot see. The value of human vision, and our brain's ability to uptake and process photons from our environment is evident by the fact that humans go to great lengths to correct their vision, either by wearing glasses, contacts, or undergoing vision corrective surgeries. Additionally, humans rely on vision for many activities that become unsafe in the absence of normal vision. As a society we have laws to require certain standards of visual acuity in order to operate vehicles, air/space craft, and other machinery. For example, advancements in AI object recognition are essential for any hope of utilizing self-driving cars in large cities.

Our squishy, fluid-filled human eye exemplifies state-of-the-art technology for achieving a hybrid of high resolution with large visual field, and technology has successfully built from this so that we now have extremely powerful methods for detecting the photons needed to artificially "see" what is happening in the world. However, our visual system currently offers un-precedented and unexplainable mechanisms for synthesizing visual form with locations in space, in relation to our own self, with absolute world coordinates, connecting past experience, present sensations, and future desired outcomes, such that we can update our own physical state at the same time as we perceive motions around us. Many scientists across the world are investigating human vision as a means to optimize human health and advance AI technologies (Beyeler et al., 2019; Chen et al., 2002; Dowling, 2005; Zhao et al., 2018).

Through the teamwork of our eyes, with our brain, the human visual system is able to act like a camera that can zoom in with high spatial resolution to certain parts of our visual field, while also still capturing the wide-field panorama. It achieves this by having photo-receptors more densely packed in the center of the retina, where light hits if it comes into the eye at a small angel. As the angle of light entering the light increases (i.e. the light is coming from visual field that is more peripheral), it encounters a lower density of photo-receptors, and photo-recepotrs that do more averaging across each other before sending their signal to higher steps in visual processing. This means that a greater number of brain signals are allocated for centrally viewed stimulus, as compared to peripherally viewed stimulus, yet there are still at least some visual signals to relay more course-grained information about our entire visual field, spanning around 90 degrees to either side of our central vision (Baars and Gage, 2010).

The emphasized central vision from the retina is propagated onwards in the brain by a complicated array of nerve fibers, through an internal brain structure called the Lateral Geniculate Nucleus (LGN), to the very back of the brain called the primary visual cortex, also known as V1. While both retinas detect information from all parts of the visual field, the neurons from each retina separate the two visual fields onto two different sides of the brain. This means that we have two separate LGN structures, and two different, entirely disconnected sets of V1 brain tissue. Information about a centrally-viewed, extended object, like a well-known human face, is split up and de-coded from two entirely separate detector-arrays. Eventually, visual information from our two brain hemispheres is re-connected at higher brain structures, but the fundamental neuron activation pattern contributes unique semantic information to each side of the brain, depending on where it is in the visual field. Figure 2.3 shows a schematic of the primary visual pathway, whereby retinal activation transports information about detected photons through LGN to the Primary Visual Cortex. The coloring in the diagram serves to both show the separation of right and left visual onto respectively left and right sides of the brain, and also to highlight the extreme nonlinearity in how central vision is magnified in its representation on the cortex. The retina is responsible for devoting increased number of pixels to central vision, and the LGN and V1 transform the location of the pixels, such that there is a different coordinate system representation of space inside the brain, which no longer aligns space in its original linear cartesian grid (Horton and Hoyt, 1991a; Olshausen et al., 1993).

Figure 2.1: **A Rose. Top Left.** Through comparing color and form to past visual sensation, our brain consciously perceives this image as a rose. **Top Right.** When the image is rotated by 15°, and the physical lines on the page are differently oriented, our brain still assigns semantic meaning of this object, as a rose. It evokes the same stored memory and the same mental associates as when the object was not rotated. **Bottom.** When the image is dilated, and the physical lines on the page are expanded to stimulate different photo-receptors in our brain and take up more of our visual field, our brain still assigns the same semantic meaning of a rose. Neural mechanisms for such flexibility of visual perception are not yet understood.

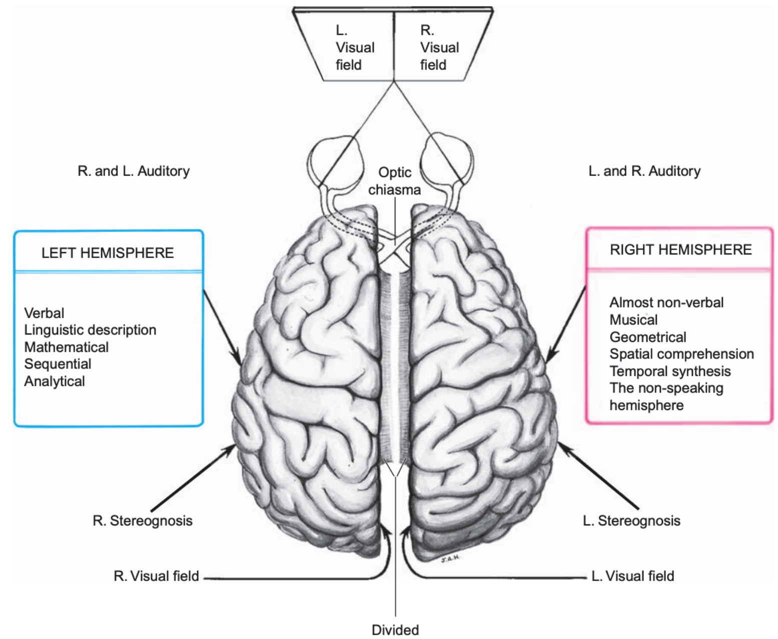


Figure 2.2: **Primary visual pathway: Retina to primary visual cortex.** Humans sense visual information by detecting individual photons that hit different parts of the retina. Photons refract through the eye such that photos from the left (right) visual field hit the right (left) side of both retinas, and photons in the upper (lower) visual field hit the lower (upper) part of both retinas. Greater eccentricity in the periphery causes activation in greater eccentricity in both retinas. All photoreceptors in the left (right) side of each retina send that information only to the left (right) primary visual cortex (V1). This means that the left and right V1 obtain completely independent information from each other. As visual information is relayed from the retina to V1, information in the center is weighted more heavily, and information in the periphery is weighted less. Additionally, the center information is sent to the posterior and peripheral information is sent to the anterior of V1. Adapted from Baars and Gage (2010).

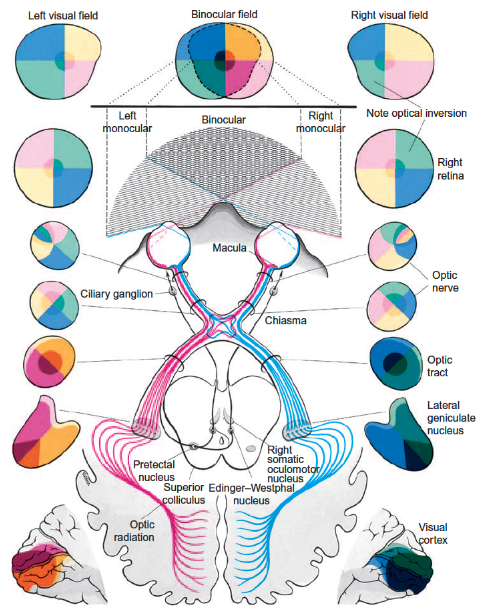


Figure 2.3: **Primary visual pathway: Retina to primary visual cortex.** Humans sense visual information by detecting individual photons that hit different parts of the retina. Photons refract through the eye such that photos from the left (right) visual field hit the right (left) side of both retinas, and photons in the upper (lower) visual field hit the lower (upper) part of both retinas. Greater eccentricity in the periphery causes activation in greater eccentricity in both retinas. All photoreceptors in the left (right) side of each retina send that information only to the left (right) primary visual cortex (V1). This means that the left and right V1 obtain completely independent information from each other. As visual information is relayed from the retina to V1, information in the center is weighted more heavily, and information in the periphery is weighted less. Additionally, the center information is sent to the posterior and peripheral information is sent to the anterior of V1. Adapted from Baars and Gage (2010).

2.2 Semantic vision is scale invariant

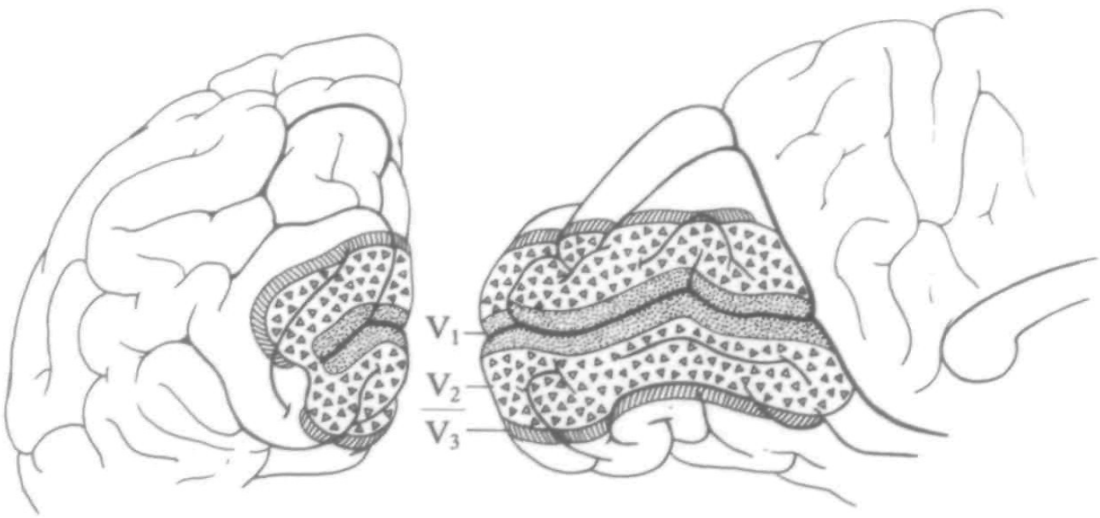


Figure 2.4: **Human primary visual cortex, left hemisphere tissue, drawing.** Drawing of left hemisphere V1 cortical brain tissue geometry and organization, along with surrounding higher level visual areas V2 and V1. The V1 brain tissue physically extends posterior to interior on the inside of each brain hemisphere, whereby the two hemispheres do not share any tissue. The horizontal midline folding of the brain tissue demarcates the mapping of horizontal midline on the visual field. The upper (lower) visual field is mapped onto the triangle-labeled tissue below (above) the fold. Adapted from Horton and Hoyt (1991a).

When you look at a circle your central vision, the pattern of activated neurons does not look like a circle in LGN or V1. Figure 2.6 shows with fMRI imaging, in the bottom images B and D, how concentric rings of a "Bull's Eye" remap into vertical striations of activation inside the primary visual cortex. Specifically, once the left visual hemisphere is mapped to the right side of the brain, and the right visual hemisphere is mapped to the left side of the brain, points in space that have equal euclidean distance from the origin are mapped into a vertical line, and points that have the same relative angle from the horizontal are mapped to the same horizontal line. In effect, the cartesian real world representation of horizontal points having same x coordinate with representation of vertical points having same y coordinate, is re-mapped, such that, now, in the brain, points having same r value are

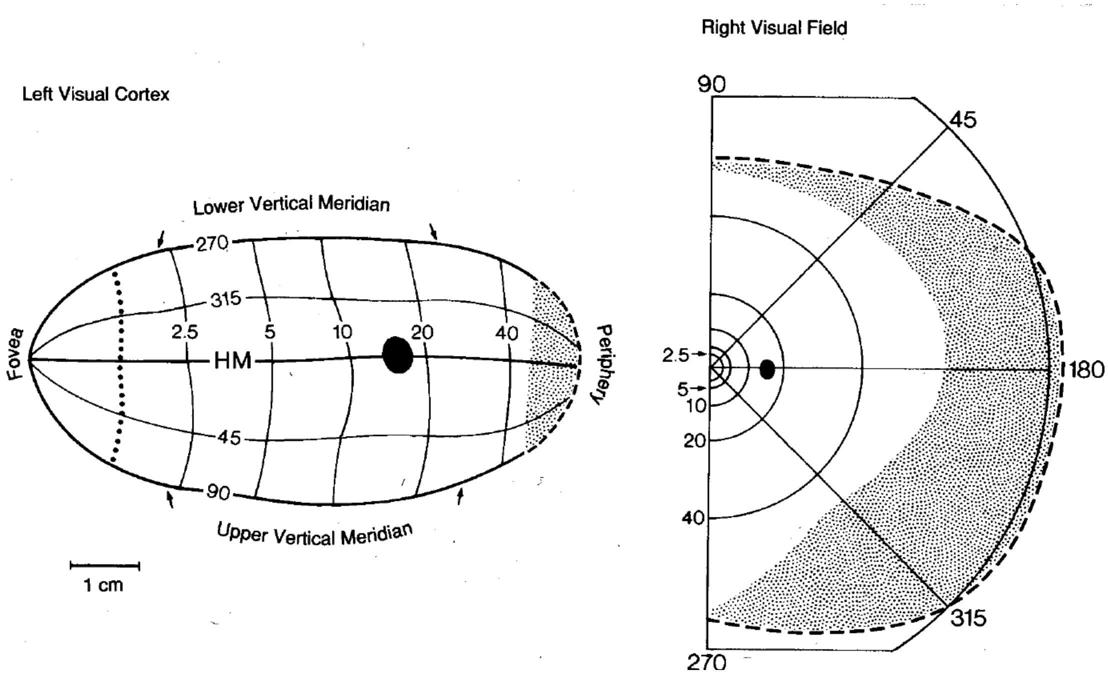


Figure 2.5: **Logarithmic polar mapping of visual field onto primary visual cortex, drawing.** Schematic demonstrating how particular regions of visual field (right side) are mapped into retinotopic but heavily center-weighted organization in V1. **Right.** Representation of visual field, with linear polar coordinates. **Left.** Representation of same regions of visual field, remapped onto physical neuronal tissue space on the primary visual cortex (V1). Peripheral field takes up physically much less space than the center visual field. Adapted from Horton and Hoyt (1991b).

mapped adjacently along one physical V1 axis, and points having same θ value are mapped adjacently along the the other (perpendicular) V1 axis. Indeed, combing the illustrations of Figure 2.3 and Figure 2.6 together, we can see that there is a *nonlinear* remapping of real world polar coordinates onto the V1 cartesian (pixel) grid. For any given location, points closer to center are given more brain space (greater number of neurons) than points farther from the center, such that there is, to good approximation, a logarithmic relationship between two locations in space, and the amount of space they take up in neuronal processing within the primary visual cortex. Formalism for mathematical models that parametrize and quantitatively showcase this nonlinearity are explicitly describe in the next section, and, here,

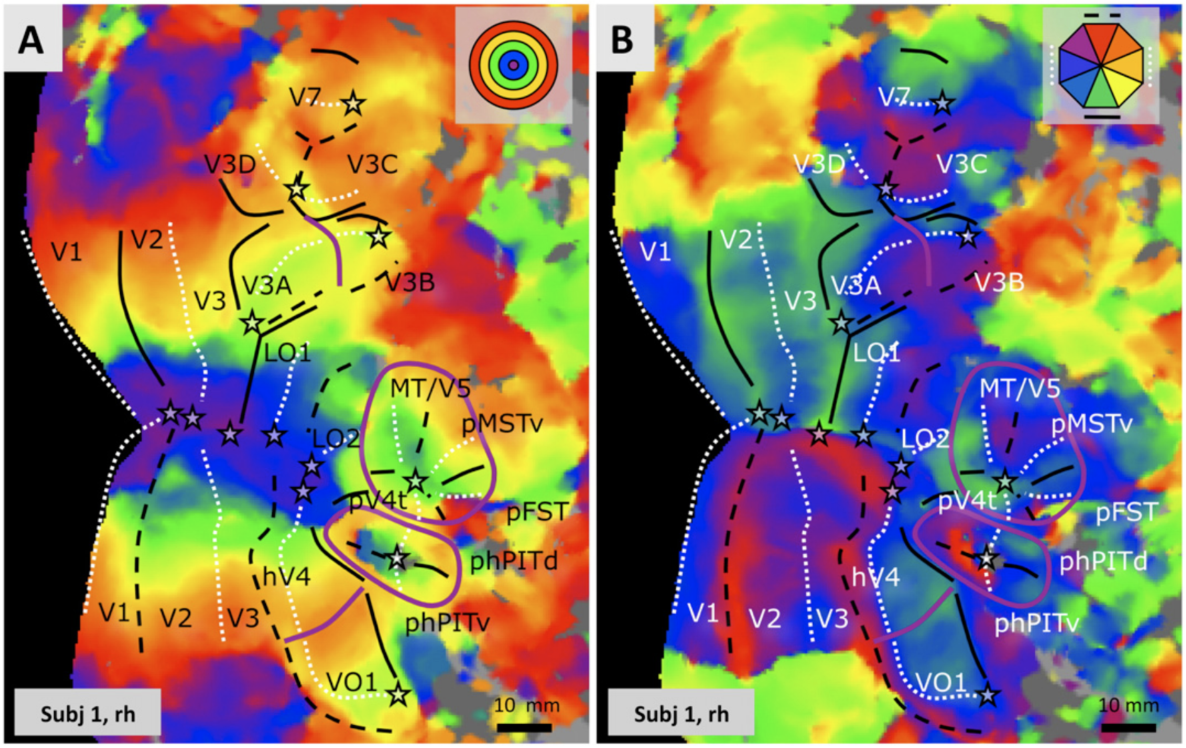


Figure 2.6: **Retinotopic mapping of human visual cortex, fMRI.** fMRI image of how information from all of visual field is mapped onto V1, and other areas of the visual cortex (Abdollahi et al., 2014).

we focus, from a contextual framework, the implications that result from such a center-heavy weighting within the brain.

This remapping, to more heavily weight the center information of an object, has been studied from the perspective of a "Cortical Magnification Factor." While cortical magnification factor has gained great success in understanding why fundament human visual spatial resolution for detection becomes increasingly poor as a function of object eccentricity, it does not help vision scientists understand how the brain makes sense of the particular neuron firing pattering that occurs on the V1 tissue from photon activation on the retina.

This is because the cortical magnification factor is scalar (magnification) property, that explains how the area region of space in the brain relates to the peripheral location of a given object of interest in the visual field. Such a mapping only accounts for the single spatial parameter of radial eccentricity, and disregards the polar angle with which the object appears on space. It also disregards information about what visual hemisphere the object is located in, which is problematic because objects in our visual field make very different neuron activation patters on our V1, depending on whether they are located in our left visual field, right visual field, or a combination of both visual fields.

If we are only concerned with being able to resolve two pixels in our visual field, then it is helpful to use the cortical magnification factor with the model for reduced spatial resolution (increased pixel size) in the brain as a function of object periphery. This would accurately predict how objects need to be larger (or two lines need to be spaced farther apart), to be discriminated, when the object is a set of two point sources, farther in the periphery.

However, since the purpose of this investigation is to understand how our brain perceives a unique and consistent pattern recognition from a variety of orientations and sizes of the same extended physical object, we must account for the vastly differing physical neuronal representations on V1. Such characterization requires maintaining two-dimensional spatial coordinate information about how each pixel in the retina is mapped to each pixel in the brain. Two objects of the same size can have different shapes, and we need to be able to consider the explicit pattern on the primary visual cortex, that supports the unique representation of information higher up in the visual processing pathways. As such, we propose to use a log-polar coordinate transformation mapping, to model how the brain processes and communicates semantic information about objects, with varying size, orientation, and position in the spatial visual field.

Physically, the transformation of the locations of an object physically in our visual field, to the locations that an object activates in our primary visual cortex, can be conceptualized by a coordinate system remapping of changing the measured cartesian coordinates of the object into planar polar euclidean distance from origin and polar angle. In this case, the origin of the coordinate system is the location of our gaze, the x coordinate is the displacement of the object horizontally from center, and the y coordinate is the displacement of the object vertically from center.

This model, inspired by the re-mapping in human visual cortex, has already been used to develop AI recognition software (Qi et al., 2006). Because AI technology does not usually involve two detectors (like we have two eyes) or two independent processors (like we have two independent hemispheres of brain visual cortex), the AI literature has predominately used a single log polar representation that employs a transformation entirely dependent on extraction of the radial and angle component of a pixel coordinate in the real world spatial map. Given a two dimensional coordinate that denotes the location of an object in space, relative to an "origin," let us label, in cartesian basis, the y axis to be the vertical displacement and the x axis to denote the horizontal displacement, respectively, of the object from the center location. As in standard log polar coordinates, the radial value and the angle value of the pixel are recorded (by using the x and y cartesian pixel value to plane polar coordinates), and then these plane polar coordinates are respectively remapped, back onto a cartesian grid, where the horizontal basis becomes the radial value, and the vertical basis becomes the angle value. The information in the exact center of the visual field is removed, and then the horizontal axis is re-scaled such that, spatially, there is a logarithmic relationship between the location representation of points in the visual field, based on their radial eccentricity. Such remapping has been shown in the AI literature to allow detectors to have increased spatial resolution in center vision, and allow for a larger range of viewing field, with reduced spatial resolution, for peripheral regions. Literature suggests that, from a detector standpoint, this offers a nice balance for AI object recognition and sensitivity across a large visual field.

More importantly, AI research shows that such logarithmic polar mapping within the brain makes it much easier for a computer processor to recognize centerally-focused objects. In this logarthmic polar remapping of the visual field onto pixel space within the first stages of computer image processing, an object that undergoes only dilation, or only rotation, has preserved pattern information on the detector. There is identical pattern on the detector, except that the object has a one dimensional translation, either entirely horizontal (for dilations) or entirely vertical (for rotations). This means that if the processor can match the object to its own trained semantic representation with much less computation power, achieving the match in shorter time with fewer resources. This AI technology was originally motivated by human eye detector information, but now, through practical implementation and computational analysis, provides insight into how the physiology of our brain might be using this particular visual mapping structure to extract semantic information.

$$x_{V1} = log\,(r) \tag{2.1}$$

$$r = \sqrt{x^2 + y^2} \tag{2.2}$$

$$y_{V1} = \theta, \tag{2.3}$$

$$\theta = tan^{-1}\left(\frac{y}{|x|}\right) \tag{2.4}$$

Here, we propose using the log polar representation of the visual field as our mapping onto V1. This mathematical transformation is simplified model of the true mapping, as in real human brains the center representation becomes slightly more linear for angles extremely close to the center and peripheral angles extremely far into the periphery. However, for the purposes of extracting out key features of human vision, we propose that the brain uses certain aspect of such logarithmic polar retinotopic mapping, to reduce the amount of processing needed to match up previously stored semantic memory, to novel photon information.

One key factor that must be accounted for in this theory, is that the brain keeps the right visual field and the left visual field information completely separated in the visual cortex processing pathway. This means that our brain's lower level visual processing structures, actually utilize a two-item parallel processing stream, whereby the two streams do not communicate whatsoever with each other, until they are both sent over the the left side of the brain into the higher level semantic visual stored memory areas of the brain, like the face fusiform area. As results, the polar coordinate system of the brain only needs to map the angle information about an object from $-90°$ to $90°$, because object information located in positive x-quadrants is mapped to an entirely different region of space than objects in negative x-quadrants of the visual field, and they do not recombine until they are presented, together, to the final states of the semantic-extraction mechanisms in higher level visual cortex.

This means that semantic representation in the brain is highly sensitive to the placement of the "origin," or the foveal eye gaze of the person looking at the object. As can be seen in the Appendix section, using the letter P as an example, under different conditions where the center of gaze is exactly in the middle of the letter, a little off-center from the middle of the letter, or just to the left of the letter.We created our own software to take input information about a character or symbol, and map it physically onto depending on the size, orientation, and location of the character in the visual field. Such software is able to be used for any symbol, in any location of visual field, and serves as unique test to see how semantic representation of an object depends on where it is located in our visual field.Such representation, as shown in Appendix, demonstrates that, there is a robust representation for an object that is rotational and size invariant in the center vision, as long as the eyes are able to fixate on the same location of the letter every time that it is presented.

However, when the object in the peripheral region, there is no way to re-create this size and rotational invariance for semantic object recognition. The object looks very different on V1, depending on its specific location in the periphery, specific orientation in the periphery, and specific size in the periphery. Given this variation of neuronal representation in V1, for the same object in different locations of the visual field, one would suspect that the brain would need to learn how to recognize an indescribable number of unique representations for every object that we semantically learn to recognize as a baby. Such theory is highly improbable, because of the sheer magnitude of number of unique semantic representations that would need to be stored in the brain. Instead, if the brain is able to extract semantic information about form and shape from peripheral objects, then there needs to a different mechanism to explain how peripheral vision actually works in the brain.

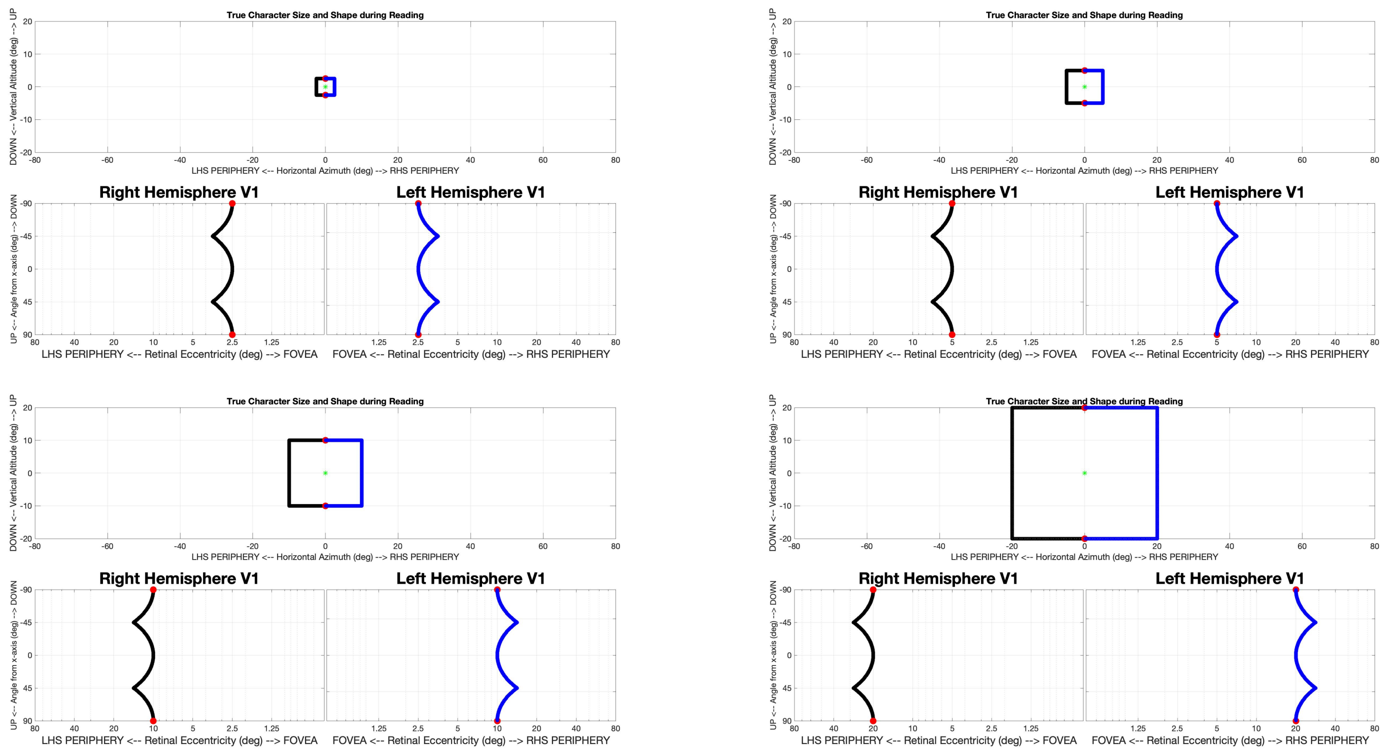


Figure 2.7: **A square on primary visual cortex, overt attention.** Model showing the pattern of neuronal activation on V1 from a square in center gaze, fovea on the empty center inside the square. Moving from the top image, downwards, the size of the object in the visual field increases and the gaze remains fixed on the empty center. Throughout the dilation of this object, the represented shape and size on V1 remains constant. The size of the object is encoded by a one dimensional horizontal shift in V1 activation.

2.3 Peripheral vision requires additional explanation

Even though our brain represents peripheral vision in a relatively distorted and comparatively reduced spatial resolution, prior experiments have shown that humans are still able to identify and extract relevant semantic information from objects that are only able to seen from locations of high retinal eccentricity (Anstis, 1974; Bouma, 1971). Yes, the spatial resolution is poorer, and so the object needs to be relatively larger, dependent on the eccentricity. But the visual processing system of the brain is still able to extract the relevant information of form and shape from the peripherally activated neurons, and connect to previously stored memory and meaning.

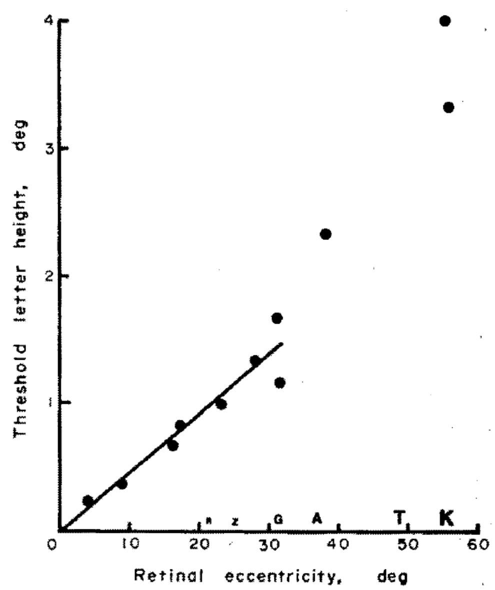


Figure 2.8: **Visual acuity dependence on periphery, without crowding, plot** In 1974, Anstis showed that humans can indeed visually recognize and report single isolated characters viewed in the periphery. This required that letters to be larger as a function of viewing angle. For eccentricity up to 30°, the best-fit linear dependence of letter height (LH) on eccentricity (e) was reported to be $LH = 0.046e - 0.031°$. The nonzero y-intercept was attributed to experimental/systematic error. Adapted from Anstis (1974)

The literature reports that we have optimal peripheral visual acuity in the case of isolated

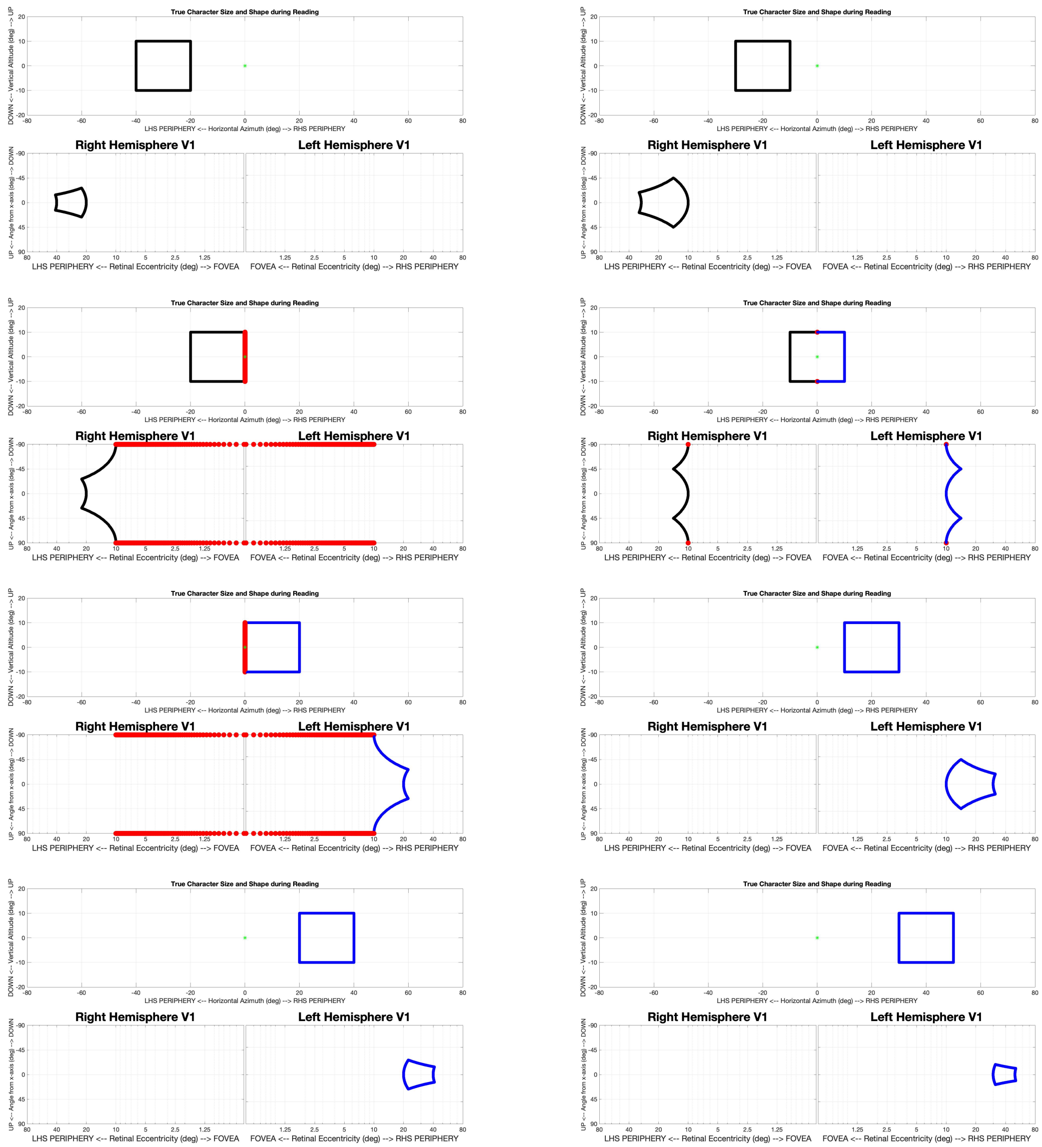


Figure 2.9: **A square on primary visual cortex, covert attention.** Model showing the pattern of neuronal activation on V1 from a square in periphery of gaze. Moving from the top-left image rightward and then downwards, line by line, the square moves from the left visual field, rightward, into the right visual field and right periphery. Through this process, both size and shape of neuronal activation drastically change on V1.

viewing conditions, where other objects are not crowding the local region of our covert attention. This means that the peripheral semantic pathway, whatever it is, is working optimally in the case of such isolated viewing conditions. Just like how engineers can put strain on a physical system to explore how it is built by assessing how it breaks down, we take a physical approach to characterizing the peripheral semantic processing pathway by stressing it with different levels of crowdedness in the visual field. We argue that there is one single mechanism that combines information from the covert attention vector and information in the peripheral field, such that the brain internally moves the peripheral representation into an attention-centered frame where rotational and dilation invariance can be used to extract semantic meaning. We propose that such mechanism is used, for any covert attention process, through any level of crowding in the visual field, whereby the success of this mechanism hinges on the accuracy of the covert attention vector. We propose that crowding specifically impairs this pathway because crowding reduces the accuracy of the attention vector. It is of our interest to parametrize the level to which this mechanism breaks down by directly comparing peripheral vision abilities with isolated character viewing, compared to peripheral vision abilities in various crowding conditions. In the first case, we hypothesize that increased crowding so that, for a given task, peripheral attention is less able to identify the correct attention vector. This means that degree of crowding should relate inversely to degree to degree of visual acuity. Increased crowding, therefore requires an increased object letter height in order to be able to covertly read at the same level of visual periphery.

As early as 1970, researchers had observed differences between foveal and peripheral visual perception (Bouma, 1971). Bouma measured the error rates, and types of error, that humans reported as their visual acuity decreased either in foveal vision or peripheral (para-foveal) vision. It was noted that as the observed character height became relatively smaller (by moving the stimulus farther away from the observer), centrally viewed objects became fuzzy, out of focus and un-interpretable, while peripherally-viewed objects became interpretable, but confusing, as they resembled different, similarly shaped characters. Such early observations showed evidence for distinct visual processing mechanisms, depending on central visual processing vs. peripheral visual processing, although at that time there was not a particular mechanism proposed.

Figure 2.10 shows foveal visual acuity, as a function of letter size, by comparing the

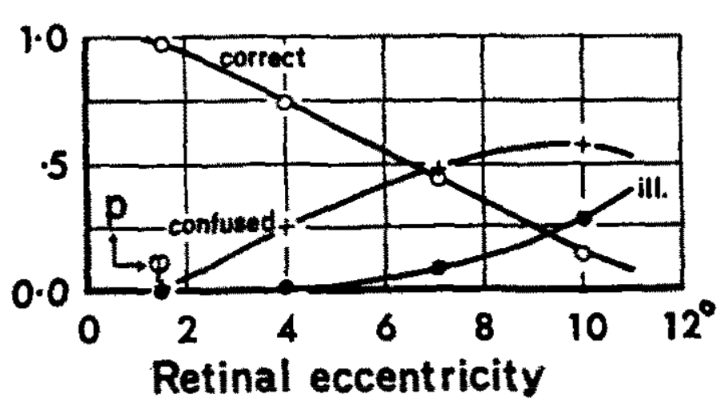


Figure 2.10: **Letter recognition accuracy versus eccentricity, plot.** As isolated letters are shown in increasingly peripheral locations, for a given letter size, percentage accuracy in letter identification reduces linearly with the degree of object periphery. However, for instances when the letter was not correctly identified, there was not a linear relationship for when the letter was incorrectly identified versus when the letter was labeled unidentifiable to any letter. Adapted from Bouma (1971).

proportion of correctly identified letters vs. the subject's viewing distance (left), and the peripheral visual acuity, as a function of letter size (right), by comparing the proportion of correctly identified letters vs. retinal eccentricity, holding the letter size fixed. In both experiments, visual acuity (isolated character reading accuracy), is reduced. Increasing the peripheral location and reducing the letter size are both ways to reduce a person's visual acuity. Past work also shows that there is around a 0.5 deg increase in letter height needed to recognize an object 10 deg in the periphery, if it was just barely discernible in the visual center (Anstis, 1974).

Additionally, it is interesting to note that subjects were far more likely to confuse peripherally presented letters as being a different letter with similar geometry, than they were to confuse letters that were presented center. Such prior findings support the idea that there is some mechanism unique to peripheral viewing, that does not occur in the case of central viewing. This also suggests that the mechanism used for making sense of peripheral information does not fail due to problems with receptive field (which would blur the image such that it becomes unrecognizable). Instead this supports the idea that the failure to recognize occurs because of some kind of image distortion that occurs, whereby edges and form are able to be extracted, but the form is not exactly the same as it should be for proper image recognition. As will be discussed in more detail in the theory section, an internal, parallel processing mechanism within the brain, may be involved to use an attention vector to internally shift the visual information such that it can be centered as if were looking directly at it in our visual field. If the attention vector is not able to correctly map, then the image will not be able to be centered correctly, and, even though the point spread function will display edges and lines, these edges and lines will appear different in the log-polar coordinate system within the visual cortex.

In particular, specific errors appeared prominent in these peripheral-paradigm experiments. There were issues of "doubling" where n was perceived as m, and v was perceived as w. There were also issues of translational shift, where a certain part of the letter appeared offset, causing confusions of b to be perceived as p and d to be perceived as q. These confusion errors were only present for the peripheral experiments, and not nearly as frequently observed for the foveal distance measurements. Specifically, through these examples it can be seen that only the vertical element in the letter was perceived to be offset. For example, p and q were not observed to have any greater likelihood of being confused in the peripheral viewing as compared to the foveal distance viewing (Bouma, 1971).

Similarly, past experiments have documented other confusions that depends on whether an upper-case letter stimulus was shown in the center, or in the periphery. Particular upper-case letter confusions occurred in just a ten degree peripheral presentation from center, that were different than the letter confusions that occurred when the stimulus was presented foveally. Moreover, the peripheral confusions were fairly consistent, independent of exactly which angle from center they were peripherally presented, inwards, outwards, or vertically (Reich and Bedell, 2000). The particular and slight differences are a source of interest through this investigation of possible peripheral attention and vision mechanisms.

There has been much work done in parametrizing how the center focus takes up more space in the V1 cortex than does periphery, with the use of a parameter called the "Cortical Magnification Factor." This factor is a dimensionless parameter that explains the scaling by which a unit area of space in the visual field takes up inside the brain (Strasburger et al., 2011). This parameter is most useful to see how much a peripheral location "shrinks" in representative brain tissue area size, compared to the that of a more center location's representation.

While we, as humans, can take pride in our high peripheral acuity under isolated conditions, we must also acknowledge that our visual field is often crowded with information. In the case of reading, for example, the page is covered in text, and we must move our eyes, with our attention, to scan the words on the page. It is here, in this condition of visual crowding, where it seems that the brain connect make sense of the same lines and shapes that it previously could in the uncrowded condition. Since as early as the 1970's researchers have been trying to elucidate the mechanism that causes crowding to confuse our brain (Bouma, 1970).

Effects of crowding were very early on constrained to super-retina effects, as crowding can still reduce peripheral visual acuity, even when the crowding stimuli are presented to a different eye than the target stimulus (Flom et al., 1963). This means that the decrease in photo-receptor density or distribution of rods and cones in the retina, are not responsible for crowding effects on reduced peripheral visual acuity. Additionally, there is evidence to suggest that even during peripheral crowding, we are able to distinguish that there are multiple objects (correctly detect presence of visual stimulus), but we are not able to focus our attention such that we can extract semantic information about form, and we are not able to use this attention to physically track the objects in space (Intriligator and Cavanagh, 2001a). This suggests that attentional limitations in periphery may lie at the heart of crowding effects on peripheral visual acuity.

Lastly, there is some evidence to suggest that criterion for whether potentially distracting information will indeed actually reduce visual acuity depends not on the size of the flanker, but how close the flanker is to the target stimulus. The notion is that this critical spacing is related to the logarithmic mapping of space onto V1 (Whitney and Levi, 2011). This observation supports the theory that receptive fields dominate our brain's ability to extract semantic information from the periphery. At the same time, if the receptive field theory is the only factor playing into our reduced peripheral acuity in crowded visual fields, then there should be much easier to see objects that are in the inside of a crowded environment, as opposed to the outer, more peripheral region in a crowded environment.

The cortical magnification theory attributes the majority of the V1 nonlinearity, as stemming from retinal photo-receptor density inhomogeneity. Since the density of photo-receptors goes down as a function of retinal eccentricity, and larger areas of photo receptors are bundled together for signal propagated onwards to the LGN and ultimately the V1, the V1 tissue naturally allocated less space for peripherally located objects. This means that the spatial resolution of our primary visual system is reduced as a function of object peripheral location, and this nature can be traced directly back to the organization of the detectors on V1. In analogy, it is as if the pixel size of our detecter increases as a function of radial distance from the center of the camera. Such theory is a bottom-up theory for vision, because it comes from the detector, and not the computer.

There is some evidence that the receptor field theory alone is not enough to describe how we can have such high visual acuity when we are viewing isolated objects in our periphery, but how acutely our vision degrades when our periphery becomes crowded. This stems from observations that humans are able to report that the recognize multiple objects, or white space between important lines, in crowded peripheral environments, but that they are unable to discriminate the semantic quality of the those lines. If the problem were only based on the reduced spatial resolution causing multiple point spread functions, of large pixels, to overlap, then human subjects would not be able to report they they can distinguish the empty space from the lines, and see distinct objects. Instead, the bleed-through form one pixel to the next would cause a grey-scale saturation that would render subject response to say that there appeared to be an amorphous blob, a single object, and not multiple pieces of information.

Such evidence against the standard receptive field model also comes from the observations that subjects are far more likely to make confusion errors when peripheral objects become difficult to recognize, as compared to when objects in central view are too small to see. There is reason to believe that a top-down mechanism may actually become the limiting factor in cases of peripheral vision semantic extraction, and that the resolution-limited receptor field theory is the dominant factor only in cases of pure psychophysical phenomenon of visual acuity object detection thresholds.

In the literature, much work has been done on measuring the receptive field of photoreceptors in the fovea compared to photo receptors that respond to peripheral visual input, as well as direct measurements on the density of receptors in the fovea compared to the peripheral regions of the retina. Given that the density of photo-receptors decline with retina periphery, as well as the fact that the receptive field increases photoreceptors in that map peripheral information, the spatial resolution of the eye degrades as a function of retinal eccentricity. This means that the information transferred to the visual cortex also loses spatial resolution as information comes from increasingly more peripheral areas of the visual field. Such an argument for receptive field dependence on eccentricity does explain why crowding can cause increases problems for visual perception in the periphery, but it does not explain all crowding phenomenon that the literature has reported on. We propose a universal mechanism for extraction of semantic information in peripheral vision, using an active mechanism for attention, that creates a vision attention vector, from the center gaze to the peripheral location centered on the target.

2.4 A new theory to explain vision

In past literature, the degradation of peripheral vision as a function of eccentricity has been attributed to limitations in photo-receptor spatial resolution, and the fact that our spatial receptive field increases, as a function of periphery. Additionally, the nonlinear cortical remapping has been characterized by a term called "Cortical Magnification Factor," that ascribes a one-dimensional scaling factor to locations in space, that map their apparent size in the visual field to their apparent size on their representation in the primary visual cortex. While these representations are valid, they do not capture the full complexity of human peripheral vision and the brain's internal representation of space in the primary visual cortex. The cortical magnification factor is a single dimensional, eccentricity dependent, magnification factor, that is only able to relate relative size between visual field objects and their representation in the primary visual cortex. It does not account for how object shape becomes changed, depending upon the object's location, size, or orientation. Therefore, it does not help to explain how an object's representation in the brain is connected to its semantic interpretation. Additionally, the cortical magnification factor does not account for the fact that there are two visual representation in the brain, pertaining to the right cortex representation of the object's left visual field appearance, and pertaining to the left cortex representation of the object's right visual field appearance. It is important to account for the specific shape of an object, as represented in the brain, depending on where the center gaze is, and the exact representation of the object on the human primary visual cortices.

Our proposed theory for vision incorporates information about cortical magnification factor within our model of the logarithmic polar coordinate transformation that occurs between real world space and the neuronal representation on the human primary visual cortex. Additionally, our theory recognizes the fundamental psychophysical resolution constrains on the human visual system that are dependent on the eccentricity of the object in the visual field. However, we do not stop there, because we want to actively characterize the mechanism by which we are able to extract semantic meaning from our peripheral visual environment, instead of focusing on the factors that might hinder our ability to do so as a function of periphery. Since we know that humans are able to extract semantic information from our peripheral environment, we strive to identify the internal brain mechanism that is responsible for this.

We propose that, for peripheral vision, the brain uses the same scale-invariant properties of a logarithmic polar representation that it uses to extract semantic meaning from central vision. However, because the scale invariant properties do not hold when an object is not centered on a logarithmic polar representation, we propose that the brain internally maps the vector from the eye gaze to the location of attention, in the spatial field. With this visual attention vector, we propose that the brain processes the visual field along the dorsal pathway, instead of the ventral pathway, in the brain, so that a cartesian coordinate system can be conserved. At an intermediate level of the dorsal pathway, a location where there are known connections to the pulvinar nucleus, we propose that the attention vector, encoded by neurons in the pulvinar nucleus, is able to be applied to the dorsal pathway spatial representation such that a translational coordinate transformation occurs to shift the spatial representation into an attention-centered representation, no longer a visual-field centered representation. In this way, the object of interest becomes centered on the brain's internal coordinate system representation. It is necessary for the brain represent the object in a linear cartesian coordinate system during this time, so that the attention vector, as a vector in linear cartesian space, can apply a translational shift to center the representation. After the image has been centered on the dorsal pathway, neurons in the dorsal pathway send the attention-centered spatial representation back to higher levels of the ventral pathway so that the attention-centered frame can be recast back into log-polar coordinates, where scale invariance can now be optimally utilized for object recognition.

Through our model, all three pathways in human vision work together, to recover semantic information about an object that is not inherently in a location where there is semantic scale invariance. The semantic ventral pathway, the spatial dorsal pathway, and the evolutionarily old visual pathways involving directly connections from the retina to the pulvinar nucleus are used, together. There is ample evidence in the literature in special cases of "blindsight" where patients with primary visual cortex legions are still able to catch objects thrown at them, and avoid bumping into things as they walk through their environment. They do not consciously report either the form or the location of an object, but they unconsciously act in such a way that shows their brain is aware of the object's presence in the spatial field. This means that there is an unconscious representation of space, facilitated directly by connections from the retina to the pulvinar, whereby the vision attention vector can be encoded. Unconscious attention is able to be located in the visual field, and compared to information about where the human gazes and body is located. Such experimental findings show that spatial vectors are mapped, stored, and communicated to other areas of the brain, by the pulvinar nucleus, already.

Additionally, while ample research in the brain's dorsal pathway for vision has been studied, we are expanding the role of the dorsal pathway to include facilitation of information relay about important objects in the periphery, such that a cartesian coordinate system can be maintained until cross-talk with the pulvinar nucleus is able to apply the vision attention vector and shift the coordinate system, from a gaze-centered representation, to an attention-centered representation. Only after the peripheral object has been internally centered, within the brain, is the brain's ventral pathway able to successfully extract the semantic information.

Such coordination of all three visual processing pathways allows for each system to operate as it has been show to do in literature, and collectively, achieve the goal of extracting semantic information from salient objects in the periphery. This theory both explains why we are able to extract semantic information when objects are presented in the periphery, and also explains why our ability to extract semantic information from the periphery depends on complexity of our visual field, around the object of interest. We propose that when objects are isolated in the periphery, like the presentation of an isolated character in the peripheral visual field, the visual attention vector is able to clearly map to the center of the object, and successfully translate the object to the center of the brain's internal visual representation. However, in the case when the visual field is more cluttered, the attention vector fails to map directly to the center of the object, and it therefore does not correctly center the object in the brain's representation, when it applies the translation of the coordinate system. In this way, prior literature on crowding effects for peripheral vision are able to be explained by the level of impairment that the local visual environment places on the brain's peripheral vision mechanism by means of limiting the accuracy of the vision attention vector. When isolated characters are shown in the visual periphery, the attention vector is at its maximal accuracy, and the vision system is limited by its fundamental, eccentricity dependent, psychophysical constraints on receptive fields and spatial resolution. When the visual environment is more crowded, the attention vector's accuracy is compromised, and peripheral vision becomes limited, not by the fundamental psychophysical constrains of the vision system as a detector, but rather it becomes limited by the attention vector's accuracy, and the ability to create a centered internal representation of the object within higher level's of the brain's visual system. Our theory makes three important predictions, which we verify through experiments and simulations discussed below. Specifically, these three predictions are in direct opposition to predictions from the passive, bottom-up theories that explain peripheral vision only by means of fundamental psychophysical limitations on peripheral receptive field and reduced spatial resolution.

Firstly, our theory utilizing the vision attention vector model for human peripheral vision predicts that human peripheral vision depends on the local level of crowding around the peripheral object of interest, not just on whether or not there is crowding around the object. This means that if a large part of the spatial field is cluttered around the peripheral target, then we predict that this clutter will have deleterious effects on the quality of the peripheral vision, by means of reduced accuracy of the attention vector. Passive, bottom-up mechanisms say that crowding impairs peripheral vision due to overlap of neighboring receptive fields, which become larger as spatial resolution reduces with periphery. In such a model, peripheral vision only depends on whether the local environment around the target is cluttered, and when a sufficient radius around the target is cluttered, sufficient to the receptive field radius, then there is maximal impairment of the peripheral vision. In this perspective, adding in additional flanking of distractors will not provide additional information that will smear into the peripheral receptive field of the target. As such, if we can show that peripheral vision is worse when there is maximal crowding in the visual environment, and there is graded performance of peripheral vision, with the radius of crowding, then we have evidence to suggest that there is an active attentional mechanism that is responsible for extracting semantic information from the peripheral environment.

Secondly, our theory predicts that attentional limitations outweigh passive psychophysical limitations, in the case of needing to extract semantic information from objects in our peripheral visual environment. Because of this, we can use background information that we know about the attention vector to predict specific cases of peripheral vision where it may be especially difficult to obtain an accurate visual attention vector. For example, it is well characterized that ballistic eye-movements overshoot, when moving from the center of gaze to a location of salience. Given that attention mechanisms involving the pulvinar nucleus have already been shown to be connected with such eye movements, we predict that the attention vector must overshoot, when mapping from the center of gaze, to a location of peripheral attention. When this quality of "attentional overshoot" is applied to our model for peripheral vision, we come to the prediction that the attentional vector will be more accurate, in the case whereby an object is located on the outer edge of a group of crowded letters, compared with if the object is located on the inner edge of a group of crowded letters. Such a prediction directly opposes the predictions of a passive, bottom-up receptive field explanation, given that psychophysics has well characterized how the fundamental spatial resolution of the visual system decreases as a function of retinal eccentricity (Fiebelkorn and Kastner, 2019; He et al., 1996; Intriligator and Cavanagh, 2001b).

Lastly, our theory of the vision attention vector offers possibility for peripheral vision to be impacted by visual crowding in locations that are not near the target. While a passive receptive field model would predict that peripheral object recognition is independent objects in a non-overlapping region of the visual field, an active theory for attention-constrained peripheral vision could explain why central crowding of characters affects peripheral vision of an isolated character in the periphery. Additionally, our model of using a log-polar internal re-mapping after an internal coordinate shift, explains particular experimental observations of letter confusions in peripheral reading. In all, our combination of theory, experiment, and simulation, offer unified mechanism and understanding of how we extract information from our peripheral visual environment.

2.5 Experimentation and simulation to test the vision attention vector theory

The literature has reported on the fact that one has better visual acuity when reporting on a more eccentric, but less crowded character in a group of letters, compared to the inner, but more crowded character. What has not been done, however, is compare two characters with equal crowding, comparing the outer character to the inner character. Our hypothesis that the attention vector is an integral part of the peripheral vision processing pathway predicts that we have may actually have higher peripheral visual acuity where our receptive field is larger, due to the fact that our internal mechanisms for attention actually overshoot to the empty space that is at a higher eccentricity, as opposed to a smaller eccentricity. This means that our internal mechanisms of attention, which research has shown may be linked to our internal mechanisms for saccadic eye movements, more easily track information near the outer edge of a group of objects, rather than information near the inner edge of a group of objects. Given the prior work which already suggests such outcomes for attention involved in this pathway, we propose that by actively comparing visual acuity of the outer letter in a group compared to the inner letter in a group, if the outer letter in the group shows higher visual acuity, then we have disproven the receptor-field theory and have shown evidence for our visual attention vector model of peripheral semantic vision. Additionally, we show that peripheral vision acuity does not depend on any level of visual crowding in the center of the visual field, suggesting that it is not important as to where our eye gaze vector is, but rather where our brain's attention vector is focused, that determines our ability to extract semantic information from a region of our visual space.

Throughout our investigation of visual acuity, we perform our experiments in such a way where we consistently compare the visual acuity of one visual paradigm holistically to the optimized viewing conditions of the isolated character visual paradigm. It is in this context that our work is the first of its kind, such that a comprehensive report on how visual crowding directly impairs the peripheral semantic extraction mechanism, as opposed to just documenting the psychophysics of visual acuity as a function of eccentricity. There is ample literature to review how crowding paradigms require an increased letter size for recognition, where the compensation for increased letter size must become exceedingly larger as one moves out to the periphery. However, more effort has been placed on documenting the letter spacing required for crowding effects, with the psychophysical focus to be documenting the letter spacing, as a function of periphery, needed to observe crowding effects. Here, we are using crowding as an independent parameter, such that we measure, for a given crowding paradigm, the degree to which we have compromised the entire peripheral vision mechanism. This is because for every crowding paradigm, we extract a single visual acuity parameter, called the normalized threshold letter height, and we compare this single parameter to the equivalent parameter under optimized isolated character viewing conditions. This means that each subject's data can be directly compared to one another, independent of the exact eyesight of each individual, Given a single peripheral processing mechanism that is wired the same in each person, we expect that there is a particular ratio whereby the average normalized threshold letter height for a given subject is a particular multiplicative constant to the average normalized threshold letter height for that same person under same viewing conditions of the isolated character visual paradigm.

In so far as we can tell, there has not yet been publication utilizing this particular paradigm of crowding conditions compared to isolated character conditions in this way. Our analysis of average normalized threshold letter height, both corroborate the findings of past literature, while also providing novel evidence that, for a fixed letter sizes, peripheral visual acuity may actually be higher when covert attention is on an outer character, compared to an inner character, in a sequence of letters. Such findings oppose the notion that the receptive field theory alone accounts for crowding's deleterious effect on peripheral vision, as well as provides support for our visual attention vector model for internally making semantic sense of information from the peripheral visual field.

Lastly, using the log-polar model for visual field to V1 spatial mapping, we directly test our theory of how the attention vector overshoots to empty space on the outside of the object of interest. Given the particular isolated character letter confusions in the literature, and the presumption that there is this single mechanism that operates at varying accuracy depending on level of crowding, then we can show that the visual confusions from the literate indeed may arise from inaccuracies in the attention vector's ability to focus on the correct location in space. We show that the attention vector's inaccuracy manifests as in internally "off-center" representation of the character, whereby the shape in the log-polar coordinate representation actually appears similar to the confused letter.

This combination of novel experiment, theoretical development, simulated neuron activation on V1, and validation of the prior literature works together to offer an updated and comprehensive perspective on how we make sense of information in our visual field.

CHAPTER 3

Experimental Methods

3.1 Peripheral Vision Experimental Protocols

In order to compare peripheral vision abilities across a range of visual stimulus conditions, many different visual paradigms were created, and tested across our subject pool. While not all subjects participated in all protocols, all subjects did have an Isolated Character (no crowding) peripheral visions session for means of comparison. Specifically, visual stimuli fit into one of four categories: Isolated Character, Fully Crowded, Peripheral (Partial) Crowded, and Center Crowded. In each of these conditions there were variants, which will be discussed in the subsequent subsections. In all of these conditions, the participant kept their gaze fixed on a center green dot, and followed the instructions to use covert attention to identify the target letter in the task. The target letter in the task would vary in horizontal peripheral angle, and the size of the letter would change, such that a critical (threshold) letter height could be obtained for each tested eccentricity, for both left and right visual fields. Figure 3.1 shows a schematic of the experimental setup. A 55' monitor (viewable display size of 138.7cm, or 54.6 inches, and panel resolution of 3840×2160 pixels) displayed a full-screen presentation of the particular peripheral vision paradigm being tested, and the participant sat, with their chin in chin-rest, to stare, as still as possible, at the center of the screen. When the stimulus would show in the periphery, the participant would, without looking at the buttons, select the button the pertained to the perceived target letter on the screen. Letter presentations were either "E," "B," or "P." The selection responses were "E," "B," "P," and "X," with "X" being the designated response for "I don't know," or "None of the other options." A single participant, in one sitting, performed up to three protocols in either a 60 minute or 90 minute study session. Subject input was recorded through a physical push button setup run by an Arduino Uno which communicated with the computer serial port via either MATLAB or Python.

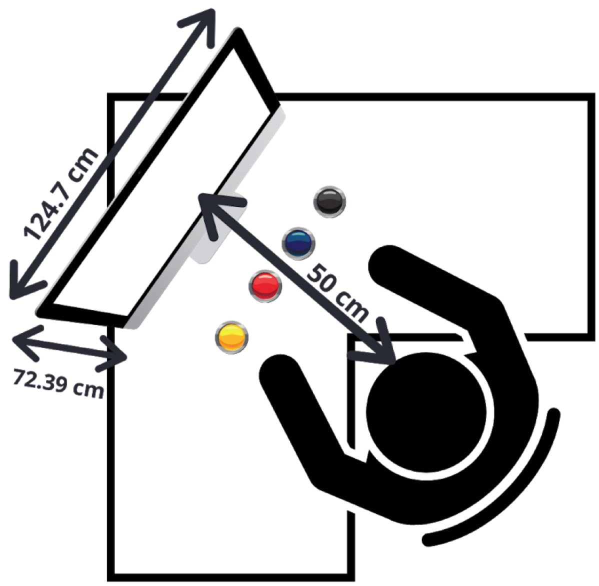


Figure 3.1: **Peripheral Vision Experimental Setup.** Participant is sitting in a chin-rest, seated 50cm away from and fixating on the center of the 55' computer screen. There are four response buttons, whereby participant can select the button corresponding to what type of character they perceive in their periphery on the computer screen. Credit: I. Suri, 2020.

The visual stimulus presentation was displayed, static, on the screen, until the participant pressed their answer selection. Once the participant selected their answer choice, the screen would refresh, and a new stimulus presentation, randomized in both letter height, letter character, and peripheral location, would appear on the screen for the next trial. In this way, we did not limit the amount of time the participant took to think or internally process to decide upon their answer selection. Instead, there was verbal instruction in the task for the participants to try to respond as quickly as possible while still prioritizing accuracy. We did not record reaction times. Stimulus protocols, depending on the paradigm, were implemented either by MATLAB's PsychToolbox or Python's PsychoPy software (Brainard, 1997; Peirce, 2007). Each peripheral vision protocol used its own experimental data acquisition script.

Final eccentricity and letter height values were saved and exported to a .CSV file, which was then analyzed offline using MATLAB, The Mathworks, Inc., Natick, Massachusetts, United States. The peripheral eccentricity of a character is defined as the subtended angle from the center green fixation dot on the screen, to the midpoint between the eyes of the participant, to the center of the character on the screen. The eccentricity angle is normal to the surface of the stimulus screen. The letter height of the letter is defined as the subtended angle from the top of the character, to the center green fixation dot on the screen, to the bottom of the character. The letter height angle is parallel (in plane) with the surface of the stimulus screen. Subjects were seated such that their eyes were 50cm displaced from the center fixation dot of the stimulus display screen.

Unfortunately, due to COVID19 precautions, we were not able to perform the complete set of study sessions originally planned, for the comprehensive external analysis of how different visual crowding paradigms impact visual acuity for a range of external and unbiased subjects. Given this constraint, the data compiled, analyzed, and presented here includes, in addition to results from external participant recruitment, internal (pilot) data that was collected to confirm experimental setup/design viability or as a an internal mock session, to train Arisaka Lab personnel for role as study session coordinators with external participants.

As a silver lining, the results obtained from internal lab testing, internal mock sessions, and external participant recruitment study sessions are all in general agreement to support our experimental claims. It is important to note that there are reports in the literature that training in visually crowded environments can yield drastically improved visual acuity results (Chung, 2007). However, our results suggest that neither our internal practice (pilot data), nor our mock session results contributed substantial opportunity for task training, and, even if there were small training improvements as a function of time, the stark differences in visual acuity across crowding paradigms was sufficiently preserved to support our scientific hypothesis and research claims.

VISUAL PARADIGM	n_{Total}	$n_{Session}$	n_{Mock}	n_{Pilot}	N_{Total}	$N_{Session}$	N_{Mock}	N_{Pilot}
Fully Crowded (FC)	**21**	**6**	**4**	**11**	**13**	**6**	**1**	**6**
1D FC (FC1)	**3**	0	0	3	**3**	0	0	3
2D FC (FC2)	**18**	6	4	8	**14**	6	1	7
Peripheral Crowded (PC)	**36**	**2**	**2**	**32**	**7**	**1**	**0**	**6**
PC, center (PCC)	**10**	1	1	8	**7**	0	1	6
PC, outer (PCO)	**9**	1	1	7	**7**	1	0	6
PC, inner (PCI)	**2**	0	0	2	**2**	0	0	2
PC, 2x flank (PC2)	**6**	0	0	6	**5**	0	0	5
PC, 3x flank (PC3)	**5**	0	0	5	**5**	0	0	5
PC, 4x flank (PC4)	**3**	0	0	3	**3**	0	0	3
PC, 5x flank (PC5)	**2**	0	0	2	**2**	0	0	2
Center Crowded (CC)	**25**	**0**	**2**	**23**	**7**	**0**	**0**	**7**
CC, 1x flank (CC)	**12**	0	0	12	**7**	0	0	7
CC, 4x flank (CC4)	**10**	0	0	7	0	0	0	7
CC, 5x flank (CC5)	**3**	0	0	3	**3**	0	0	3

Table 3.1: **Complete subject pool for all crowding paradigms.** This table shows the complete breakdown for number of pilot sessions, mock sessions, and study sessions, for each crowding paradigm. n is the number of total sessions obtained in a particular visual crowding paradigm and N is the number of unique subjects that whose data contributed to results for the visual crowding paradigm.

3.1.1 Isolated Character Visual Stimulus

In the control session block where Isolated Characters were shown in the peripheral field, letters were randomly presented at pre-set eccentricity values, such that the critical letter height could be found for each of those discrete peripheral locations in the visual field. Peripheral locations, on both the left visual field and the right visual field, ranged from 0-40 degrees, tested in increments of 5 degrees. Letters were displayed on the computer, as in image, using Arial font, from Microsoft Word. Figure 3.2 shows an example of an Isolated

Character visual stimulus, where the correct answer choice would be the letter "P."

Figure 3.2: **Isolated Character (IC) visual stimulus, example.** Example isolated character paradigm visual stimulus shown on the computer screen. Task required participant to keep steady gaze on the center green dot, and respond, as accurately as possible, regarding what character was displayed in the periphery.

In order to find the participant's critical letter height for each peripheral location, a real-time, stair-case algorithm was used, that adjusted the next trial's letter height, based off of whether the participant was correct in their response on the current trial. If the participant was correct in their answer, then the letter was slightly smaller at that eccentricity for the next presentation. If the participant was incorrect in their answer, then the letter was slightly larger at that eccentricity for the next presentation. Overall, the algorithm settled on a final letter height for a given eccentricity (converged) under two possible conditions. The first possible condition for convergence was when the participant experienced three consecutive "reversals," meaning that the participant answered correctly for a given character letter height, incorrectly when the letter height was at its next smallest height option, and then correctly again on the third trial where the character was back to the original letter height.

Likewise, conditions for convergence could also be achieved when the participant answered incorrectly for a given character height, correctly when the character was increased to the next possible smallest increase in letter height, and then incorrectly, on the next trial when the letter height returned to the slightly smaller value. Once convergence was established for a given right and left presentation of particular peripheral angle, a different peripheral angle was randomly selected from the remaining available options, and the stair-case algorithm was run again, to measure the new letter height for convergence at this given eccentricity value.

the participant was correct 50% of the time, for that letter height at that eccentricity. White letters were shown on a dark grey background, with projected light from the monitor creating photopic visual viewing conditions. Once a staircase had successfully determined the critical letter height for a participant at one peripheral angle, the participant was allowed a 10-30 second blink break before the next mini-block to find the critical letter height at a different peripheral angle.

3.1.2 Fully Crowded Visual Stimulus

In the experimental study session block where a Fully Crowded visual stimulus was presented, an entire screen full of letters was shown, all at the same time, on the screen. The participant was situated in identical fashion as to the IC control session, with eyes fixed on the center of the screen for the entire duration of the session. However, because all the letters on the screen appeared at the same time, the task was different than that of Isolated Character. In the Fully Crowded visual stimulus paradigm, the participant was instructed to report the letter directly adjacent to the center green dot, along the direction of the arrow that appeared inside the dot (either pointing left or right). Based on the participant's response, the participant would either be instructed to report the next letter one location peripheral to the previous location (if their previous response was correct), or to start a new trial, with letters of a different size and potentially different reading direction (if their previous response was incorrect).

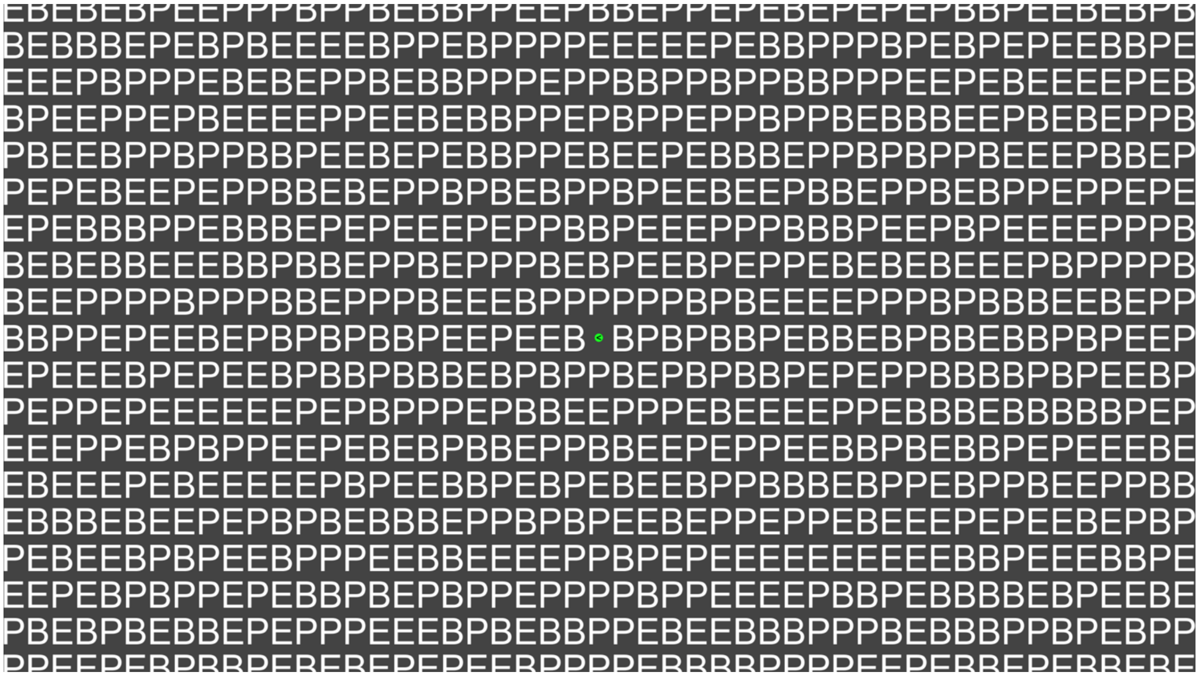


Figure 3.3: **Fully Crowded (FC) visual stimulus, example.** Example Fully Crowded paradigm visual stimulus shown on the computer screen. Task required participant to keep steady gaze on the center green dot, and respond, as accurately as possible, regarding what character was displayed, moving in a line outwards from the center dot, in the direction that the arrow pointed inside the center dot.

There were two different visual paradigms that we used with Fully Crowded Peripheral Vision task. In the first case, the stimulus looked of similar form to Figure 3.3, with the entire screen a two-dimensional array of characters. This stimulus paradigm is referred to as Fully Crowded, 2-Dimensional (FC, 2D). In an alternate stimulus presentation, the stimulus only contained three rows of characters, in only half of the screen. Instead of using the center arrow in the fixation cross to determine the direction for peripheral reading, the asymmetry of letters on the screen determined the direction of reading. This stimulus paradigm is referred to as Fully Crowded, 1-Dimensional (FC, 1D), since the target letter is maximally crowded along one direction (horizontal), but not maximally crowded along the other direction (vertical).

In these Fully Crowded visual paradigms, the independent (fixed) parameter in the experimental methods was letter height, while the independent (measured) experimental parameter was eccentricity (how far out the participant was able to correctly read the string of letters). The participant repeated the same task of reading along a given horizontal direction in the fully crowded randomized array of letters until they made a mistake. The eccentricity of the center of the mistakenly reported letter was recorded. Upon the participant's error, a new, randomized array of letters appeared with a random (either right or left) direction for reading. Letter height for a given array ranged from 0.25 degrees to 3.75 degrees, in increments of 0.5 degrees, and ranged from 5 degrees to 10 degrees in increments of 1 degree. All text was displayed using Helvetica font, from Microsoft Word.

3.1.3 Periphery Crowded

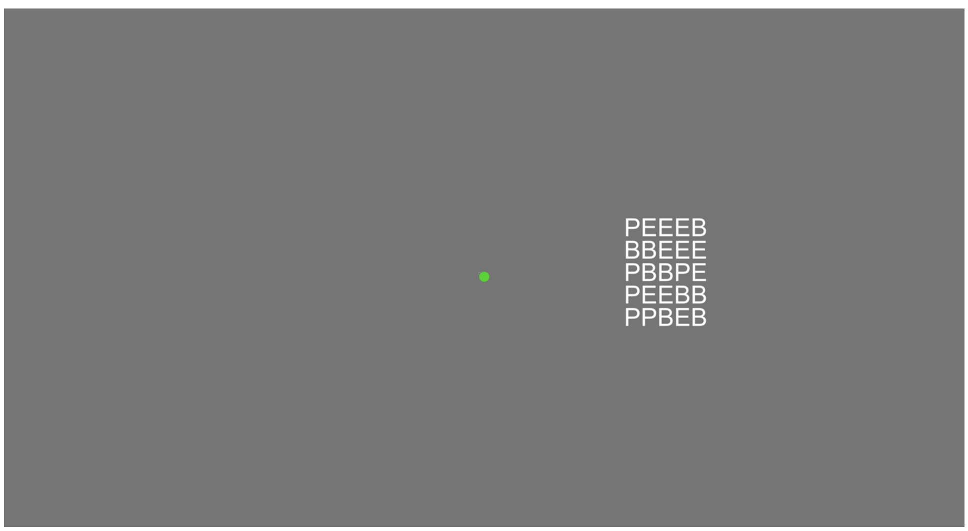


Figure 3.4: **Peripheral Crowded Partially (PC) visual stimulus,** 5×5 **example.** Example peripheral crowded paradigm visual stimulus, as shown on the computer screen. Task required participant to keep steady gaze on the center green dot, and respond, as accurately as possible, regarding what character was displayed in the center of the boxed cluster of letters in the periphery. In this particular example of visual stimulus, the stimulus was a 5×5 box of letters, such that the center target letter was flanked on all sides by two laters of additional letters.

Experimental study session visual stimuli were also used, which contained an intermediate level of peripheral crowding. These "partial" crowding stimuli served either as a comparison test for the Fully Crowded visual stimulus, or as an independent measurement of how peripheral vision abilities depended on the location of the target character, within the cluster of letters. In the first case, the stimulus is referred to as having a partially crowded periphery, and the level of crowding around the center target varied from having two layers of letters form an additional "box" around the target character (5×5 box of letters), to having five additional layers of characters (11×11 box of letters) "box" the target letter. Figure 3.4 show an example of a visual stimulus with a 5×5 periphery crowded paradigm. In the second case, the stimulus is referred to as having a periphery crowded "cross," whereby a letter at a given peripheral location is flanked by four other random letters, above, below, to the left, and to the right. In all tasks, the peripheral location of the center letter is recorded, while the target letter changes. Figure 3.5 show an example of a visual stimulus with a "cross" periphery crowded paradigm. The "cross" visual stimulus was used for three different peripheral vision tasks. In the first case, the center letter was the target letter. In the second case, the inner letter was the target letter. In the third case, the outer letter was the target letter.

In all peripheral crowding visual stimuli conditions, the stimulus was displayed at randomly selected peripheral eccentricity in the range of zero degrees to 40 degrees, in increments of 5 degrees, along the horizontal axis. Data from zero degrees was not used. The same staircase algorithm was used as described in the Isolated Character visual stimulus protocol paradigm. For the Peripheral Crowded (block) visual stimulus, the center target letter was flanked by either two, three, four, or five layers of letters. This meant that the stimulus protocol task was to identify the letter at the center of, respectively, either a 5×5, 7×7, 9×9, or 11×11 block of letters. The background color and letter colors were identical to that used in the Isolated Character Protocol, and the task rules/ protocol for breaks were otherwise also the same.

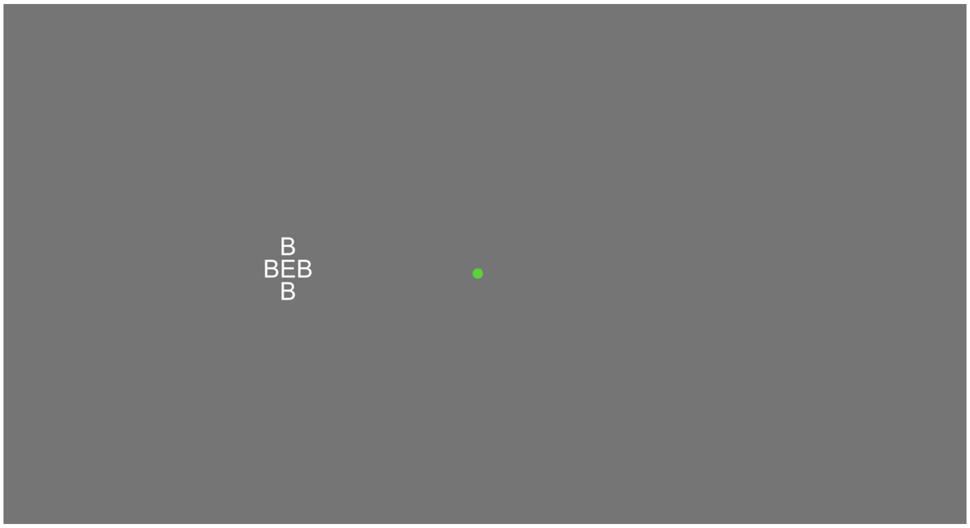


Figure 3.5: **Peripheral Crowded (PC) visual stimulus, cross example.** Example peripheral crowded paradigm visual stimulus, as shown on the computer screen. Task required participant to keep steady gaze on the center green dot, and respond, as accurately as possible, regarding what character was the target character. Depending on the task of that particular study session block, the target character could be the center character (PCC), the inner character (PCI), or the outer character (PCO).

3.1.4 Crowded Center

The final category of stimulus presentation that was used for this study consisted of the Isolated Character protocol, with the addition of a group of random letters also presented in the center of the viewing frame, where the participant was fixing their gaze. This stimulus presentation is referred to as a Crowded Center viewing paradigm, and has several subcategories of stimulus, whereby the spread of crowded center character was varied. The "crowded center" consisted of presenting, in addition to the Isolated Peripheral Character, a random letter to the center that was flanked by either a single layer of letters (3×3 grid of centrally displayed letters), a 4-level layer of letters (9×9 grid of centrally displayed letters), or a 4-level layer of letters (11×11 grid of centrally displayed letters). In all other ways, this task was identical to the Isolated Character visual crowding paradigm Task.

3.2 Study Recruitment and IRB Approval

For the Arisaka Lab visual acuity study, an independent IRB was constructed and approved, which awarded a small amount of course credit to Physics 5 Series students for their consent and participation in a 60-90 minute study session. All non-internal study recruitment, study session methods, and data analysis methods were approved by University of California, Los Angeles Institutional Review Board IRB#19-000751. If students desired, they were able to apply the course credit awarded towards the points they would receive in completion of their post-quarter (60 minute study session) or mid-quarter and post-quarter surveys combined (90 minute study session). This meant that students always had the choice of how they wanted to achieve these points, and only a small fraction of the total student population was interested at any given time. We were careful to only advertise this credit option to the course (either 5A, 5B, or 5C) which was not being actively taught by any graduate students or professor associated within the Arisaka Lab. Students were recruited via their laboratory section GradeScope email notifications, at the beginning of the quarter, in the middle of the quarter, and again at the end of the quarter, before their end of quarter survey submissions were due.

3.3 Funding

This work is supported by the UCLA Department of Physics and Astronomy, UCLA Division of Physical Sciences, UCLA Division of Life Sciences, and UCLA Center for Advancement of Teaching (CAT), formerly known as the UCLA Office of Instructional Development (OID), under two UCLA IIP Grants: *Physics Optimized for Life Science Majors: New Course Development of Physics 5 ABC and Labs*, AY17-18, and *Data-driven, Systematic, and Sustainable Transformation of Physics for Life Scientists*, AY18-19. All experimental study design, assessment, and analysis was in accordance with the University of California, Los Angeles Institutional Review Board (IRB #19-000751, *Visual Acuity and Microsaccades* and IRB #19-000578, *Assessing Physics for Life Sciences*).

CHAPTER 4

Experimental Results

Our crowding experiment results provide evidence to support that graded level of crowding is monotonically correlated with the quality of peripheral semantic visions. We also find support that the inner character recognition is more compromised than the out character recognition. Lastly, we find potential evidence that the 2D Fully crowded visual paradigm may impact peripheral vision performance slightly more than 1D Fully Crowded visual paradigm. We also find interesting evidence that center crowded visual paradigms may actually support the quality of peripheral vision, although this is not found to be statistically significant. Table 4.1 shows all average normalized threshold letter height (mean slope of letter height versus eccentricity), for every crowding paradigm that we tested in our peripheral vision experimental study. Along with the visual paradigm description and average normalized threshold letter height (mean slope), standard deviation of the calculated best fit mean slope (SD), standard error on the mean of the calculated best fit mean slope (SEM), and total number of samples (session) used in the calculation (n) are shown.

VISUAL PARADIGM	mean slope	SD	SEM	n
Fully Crowded (FC)	**8.45**	**1.73**	**0.38**	21
Fully Crowded, 1D (FC1)	7.44	0.89	0.51	3
Fully Crowded, 2D (FC2)	8.62	1.79	0.57	18
Peripheral Crowded (PC)	**3.28**	**0.99**	**0.17**	36
PC, center (PCC)	3.11	0.67	0.21	10
PC, outer (PCO)	2.30	0.68	0.23	9
PC, inner (PCI)	2.78	0.79	0.56	2
PC, 2x flank (PC2)	4.36	0.56	0.29	6
PC, 3x flank (PC3)	4.14	0.50	0.22	5
PC, 4x flank (PC4)	3.57	1.31	0.76	3
PC, 5x flank (PC5)	4.79	0.29	0.21	2
Center Crowded (CC)	**0.94**	**0.22**	**0.04**	12
CC, 1x flank (CC)	0.89	0.15	0.04	2
CC, 4x flank (CC4)	0.97	0.28	0.09	10
CC, 5x flank (CC5)	1.05	0.25	0.14	3

Table 4.1: **Average normalized threshold letter height ratio for all visual crowding paradigms.** This table shows the average normalized threshold letter height for each of the visual crowding paradigms tested in this study. SD is the standard deviation on the average slope and SEM is the standard error on the mean (SD/$\sqrt{n}$), where n is the number of trials for that crowding paradigm.

4.1 Peripheral Crowding Effects

Figure 4.1 specifically shows, on a single subject level, how the Fully Crowded visual paradigm raw data, as compared to the partial periphery crowded raw data, has a much higher average normalized letter height (mean slope of Letter Height vs. Eccentricity). In our results, there is support for a relationship between means lope and level of peripheral crowding in the visual paradigm. For more statistics information, including the reduced chi square values for the linear fits, and tests for data normality, see Table A.1.

When the single subject data are grouped together, and multiple-subject results are combined the data continue to show stark contrast between peripheral vision abilities in the fully crowded and partially crowded visual crowding paradigms. Figure 4.2 with Table 4.1 both show the monotonically decreasing relationship between level of crowding and quality of peripheral vision.

Additionally, Figure 4.3 shows combined representation of all of our subject data, including pilot data, mock sessions, and study sessions, whereby the average normalized letter height RATIOs are plotted, to compare each study session's peripheral vision measurements agains that same subject's isolated character peripheral vision measurements. In figure 4.3, it can be seen that the fully crowded visual paradigms have a statistically significant stronger impact on degradation of peripheral vision, as compared to the partially peripherally crowded experimental paradigms. The average normalized letter height RATIO for the Fully crowded paradigms was 8.44 and the average normalized letter height RAIO for the partially peripherally crowded paradigms was 3.28 ($P = 2.02 \times 10^{-10}$)

Control data, showing how the results depends on the type of study session (pilot, mock or internal) can be found in Figure A.1 and Figure A.2, which shows that our pilot data, mock sessions, and study session results were all consistent in the average normalized letter height RATIO for each type of crowding paradigm.

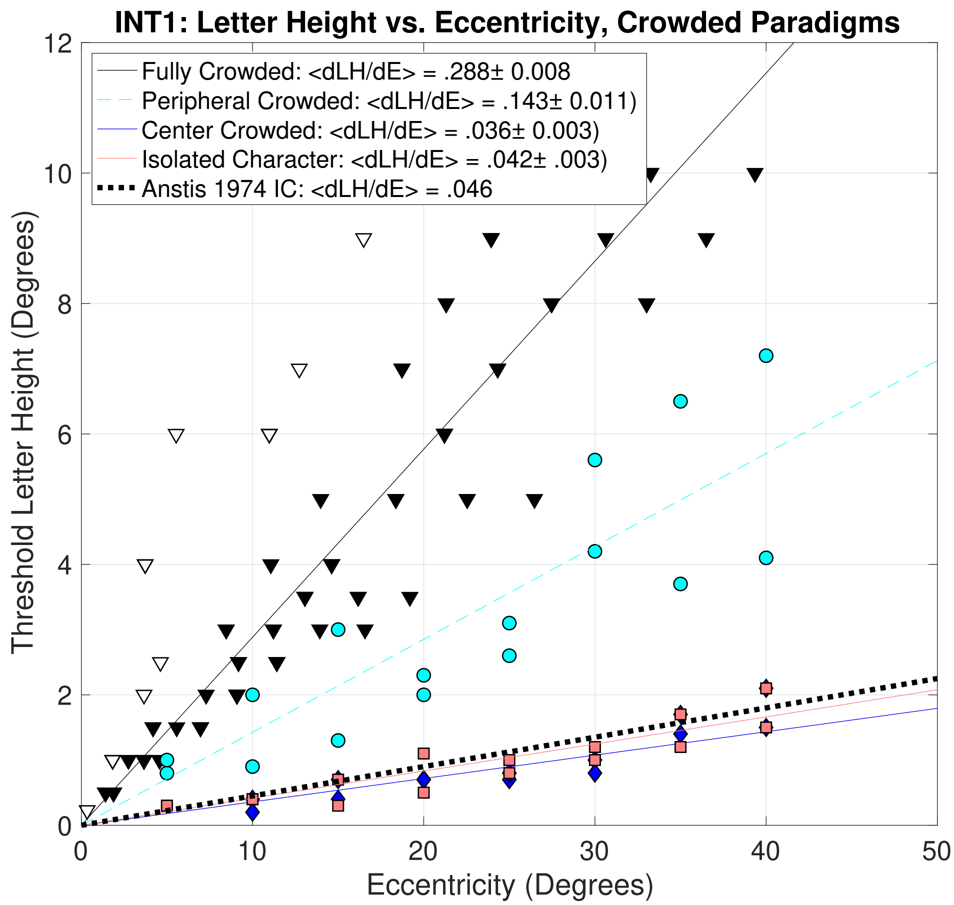


Figure 4.1: **Average Normalized threshold letter height, across crowding paradigms, INT1.** This figure shows single subject data for Threshold Letter Height vs. Eccentricity, comparing fully crowded, partial periphery crowded, and center crowded trials, against Isolated Character letter height thresholds. The literature reported isolated character data is plotted as dotted line for comparison, to show agreement with our results.

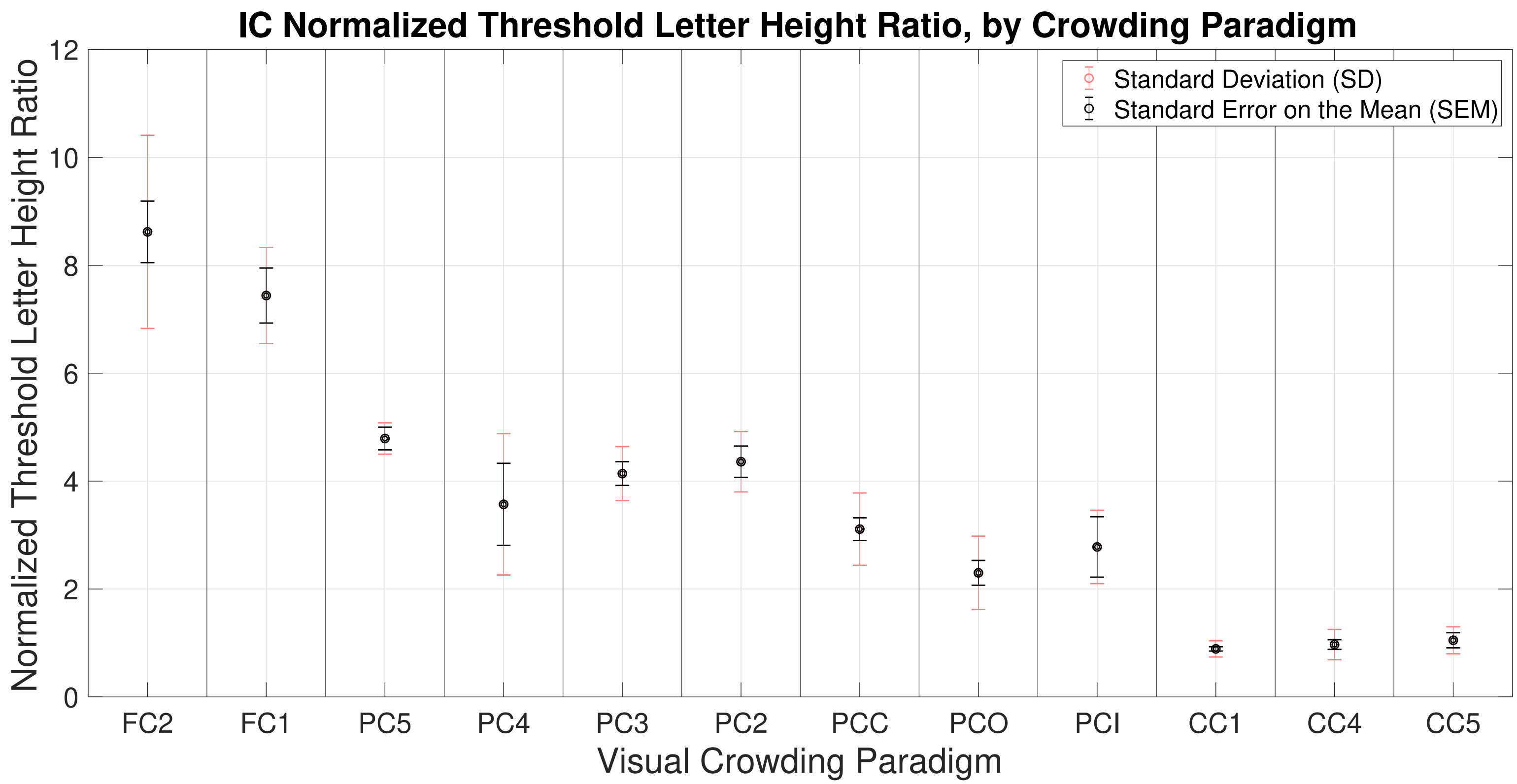


Figure 4.2: **Average normalized threshold letter height ratio for all visual crowding paradigms.** This plot shows the average normalized threshold letter height for each of the visual crowding paradigms tested in this study. SD is the standard deviation on the average slope and SEM is the standard error on the mean $(\mathrm{SD}/\sqrt{n})$, where n is the number of trials for that crowding paradigm.

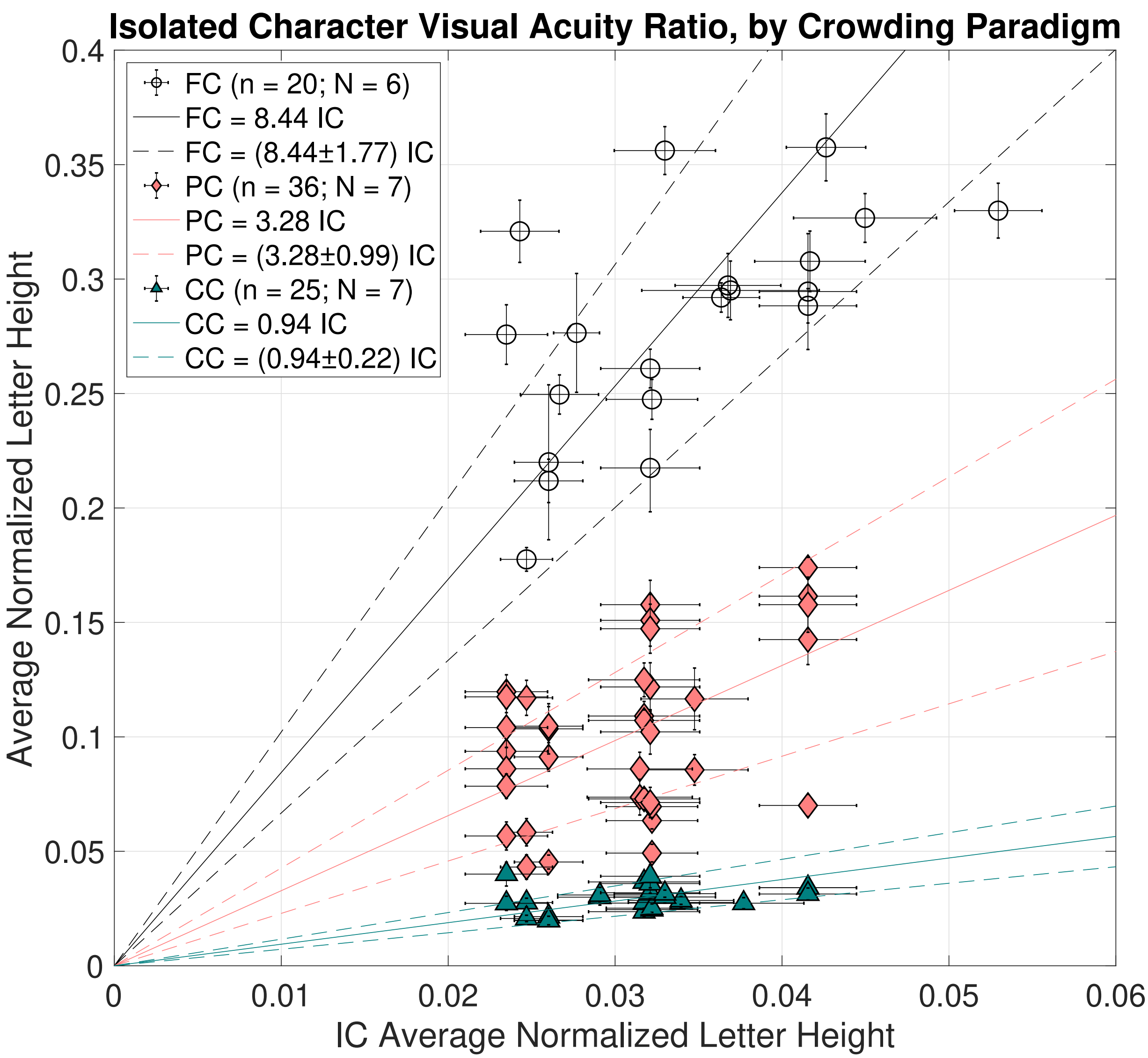


Figure 4.3: **Normalized threshold letter height ratio, comparing FC, PC, and CC trials.** This plot shows normalized threshold letter height ratios across all subjects in the study, comparing FC, PC, and CC trials. FC has the largest average normalized threshold letter height ratio, PC has an intermediate threshold letter height ratio, and CC has the smallest average normalized threshold letter height ratio, around unity.

While it is clear that the fully crowded visual paradigms require a larger letter height than the partially peripherally crowded visual paradigms, for the same level of eccentricity, it is not as clear whether there is statistically significant difference between the specific types of fully crowded visual paradigms, and between the specific types of partially peripherally crowded visual paradigms. Figure 4.4 shows the comparison of 1D Fully Crowded Peripheral vision results, as compared with the 2D Fully Crowded Peripheral vision results. While our N = 3 means low statistics, and our results are not statistically significant, there is evidence that the 1D Fully crowded paradigm may compromise peripheral visions less than the 2D Fully Crowded paradigm. However, even if the result is fount to be statistically significant with a future larger subject pool, this results is not nearly as large of an effect size, as the comparison between either 2D Fully Crowded or 1D Fully crowded, compared to the partial periphery crowded visual paradigms.

Lastly, we consider differences in peripheral visions, between the different levels of partially peripheral crowding, that we test, with our participants. Figure 4.5 shows comparison, across all subjects, of average normalized letter height RATIO, for all partially peripherally crowded visual paradigms where the target was in the center of the crowded cluster. There is not a statistically significant trend of peripheral vision impairment, from low to high levels of crowding, that depends on the radius of the crowding perimeter of text that surrounds the target letter. As expected, the partially crowded paradigm where the central letter is flanked by a cross, instead of a full box, handicaps peripheral vision less than the other crowding paradigms, where the target letter is completely surrounded by at least one full box of flanking letters.

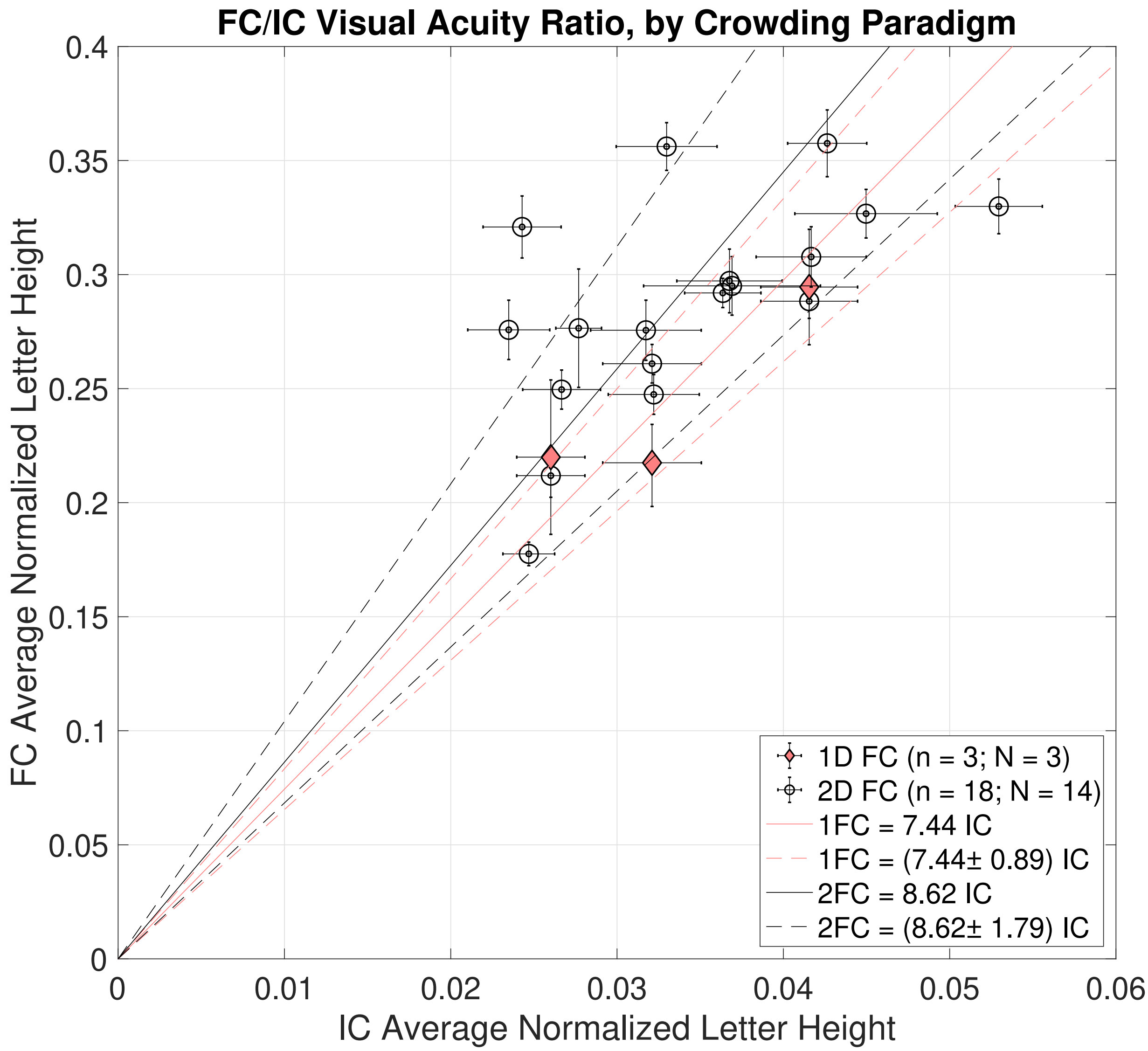


Figure 4.4: **Normalized threshold letter height ratio, comparing 1D and 2D FC trials.** This plot shows normalized threshold letter height ratios across all subjects with FC results, separated by specific crowding paradigm. 1D FC yields a smaller ratio than 2D FC, on average.

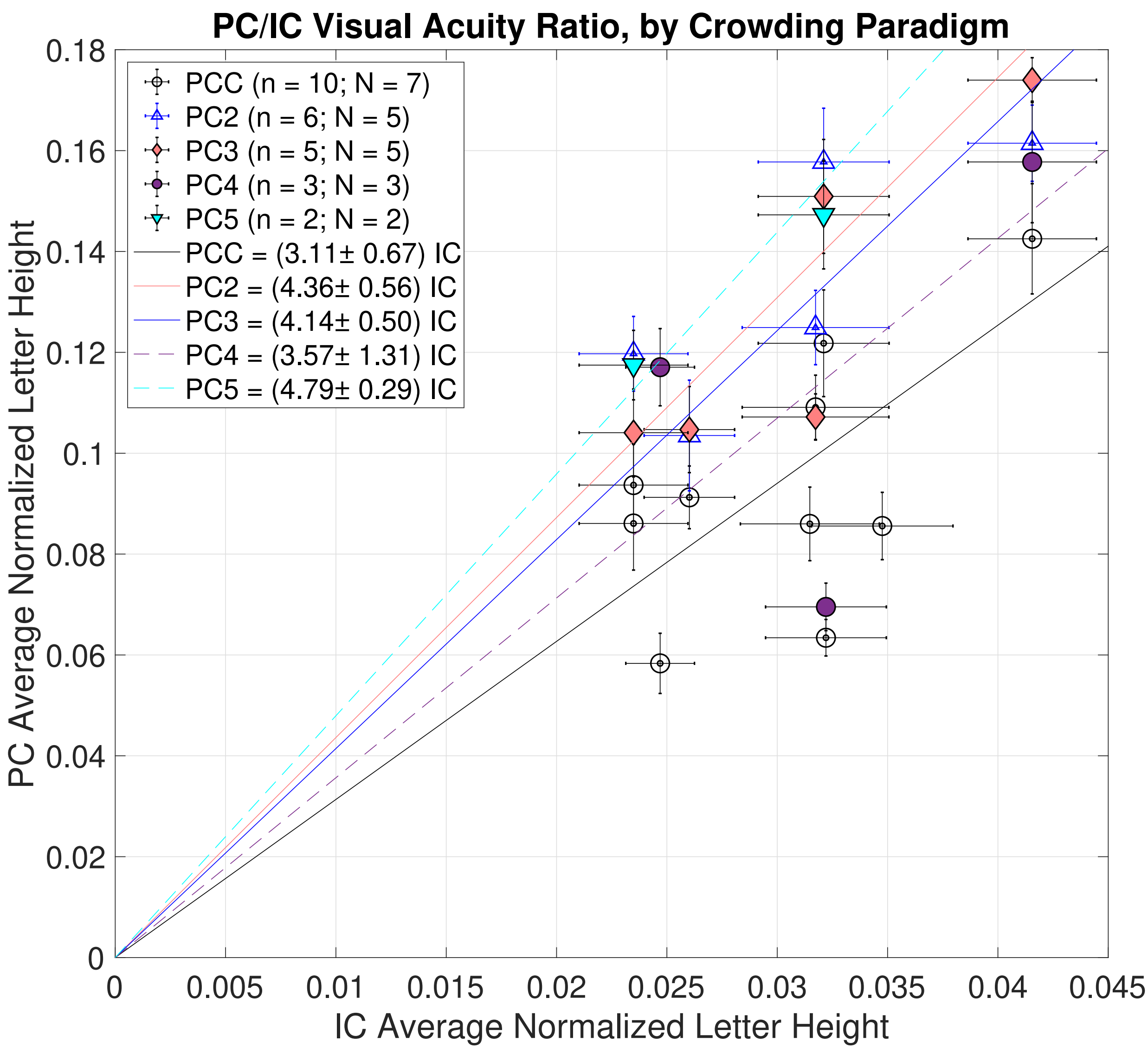


Figure 4.5: **Normalized threshold letter height ratio, comparing CPC, CP2-CP5 trials.** This plot shows normalized threshold letter height ratios across all subject CPC, CP2, CP3, CP4, and CP5 trials, separated by the crowding paradigm. On average, CPC yields the smallest average ratio, with no significant trend among the other, higher intensity crowding paradigms.

4.2 Peripheral Vision for Inner vs. Outer Targets

Next, we compare peripheral vision results for inner targets, as opposed to outer visual targets, given that the overall crowding geometry of the stimulus is the same across all tasks. Figure 4.7 shows results comparing periphery crowded, center target, periphery crowded, outer target, and periphery crowded, inner target average normalized letter height for one subject, across the different visual crowding paradigm tasks. For this subject, the inner target crowding task proved to degrade peripheral vision more than the outer target crowding task. Central target task had average normalized letter height of 0.86, inner target task had average normalized letter height of 0.78, and outer target task had average normalized letter height of 0.057. The difference between target inner and target outer was statistically significant ($P = .012$).

Figure 4.7 shows results comparing periphery crowded, center target, periphery crowded, outer target, and periphery crowded, inner target average normalized letter height RATIOs across all subjects with data for any of these categories. As can be seen from these data, we had only two subjects with crowded periphery, inner target data, so we are looking forward to following up on this with more statistics in the future. While both outer and inner tasks show better peripheral vision results than the center target task, the results show evidence that the inner task requires a larger normalized letter height than the outer target task, for the same visual stimulus.

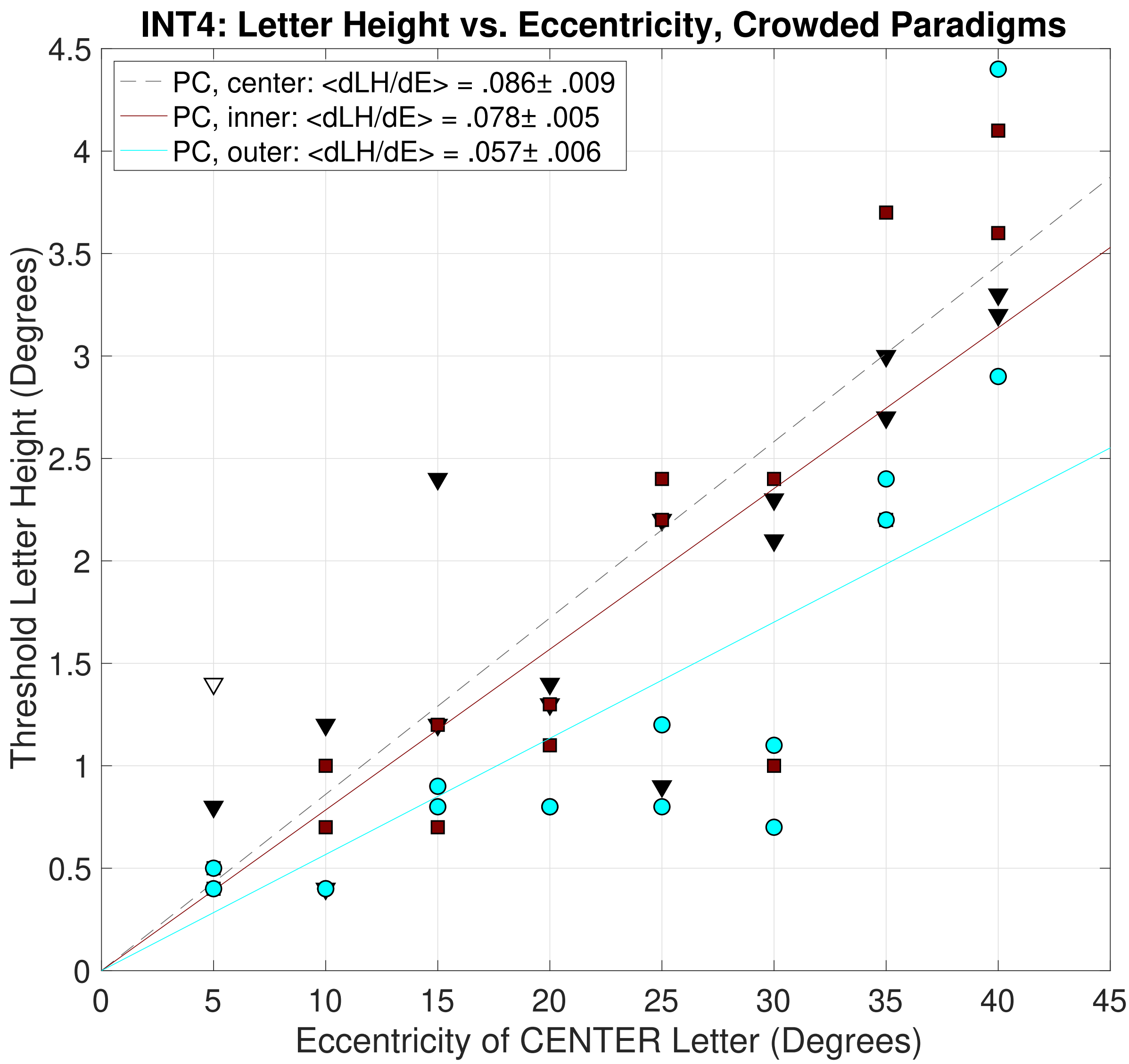


Figure 4.6: **Normalized threshold letter height, comparing CPC, CPO, and CPI trials, INT4.** This plot shows normalized threshold letter height, for a single subject, across trials with CPC, CPO, and CPI results, separated by specific crowding paradigm. Central target task had average normalized letter height of 0.86, inner target task had average normalized letter height of 0.78, and outer target task had average normalized letter height of 0.057. The difference between target inner and target outer was statistically significant ($P = .012$)

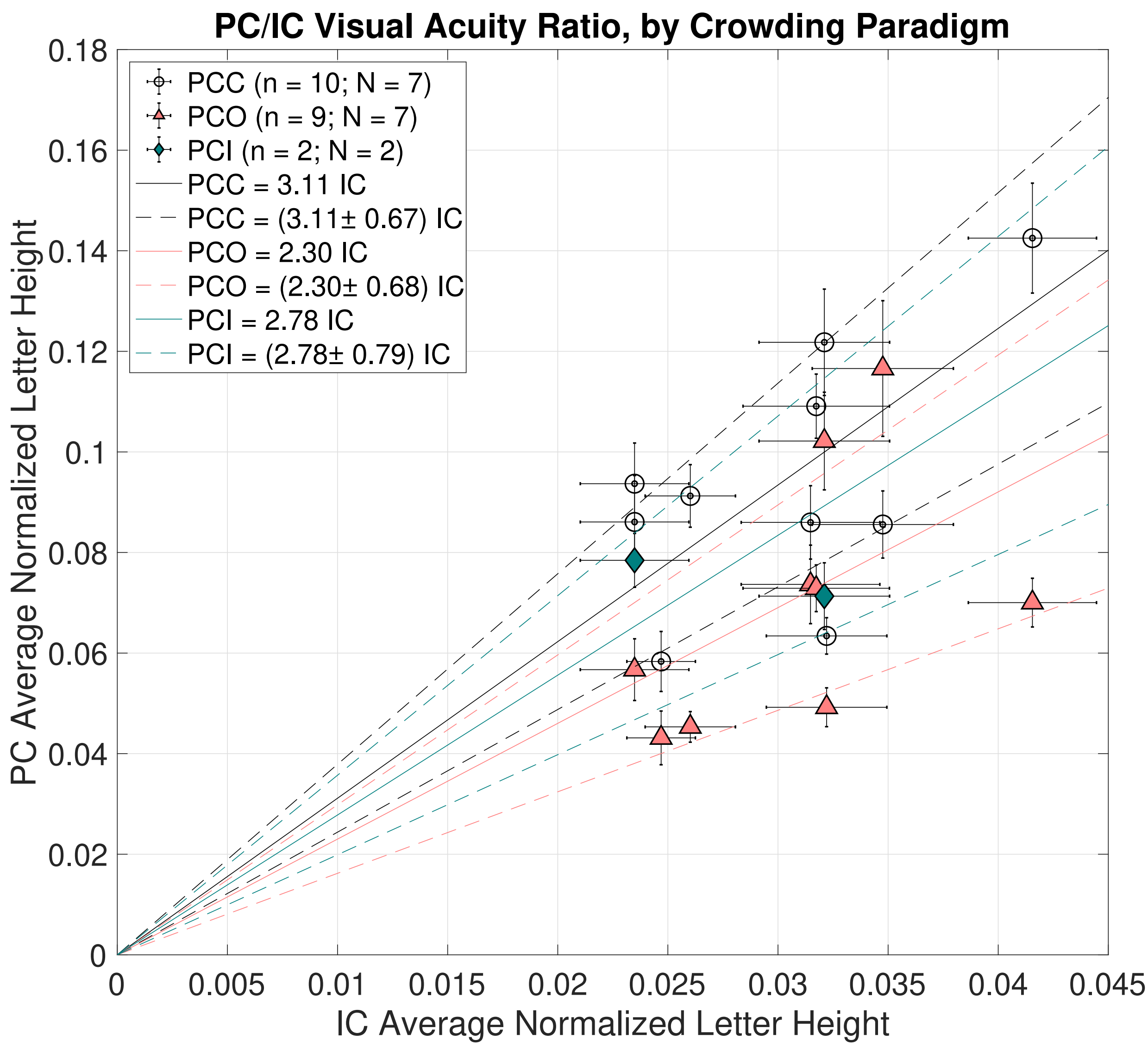


Figure 4.7: **Normalized threshold letter height ratio, comparing CPC, CPO, and CPI trials.** This plot shows normalized threshold letter height ratios across all subjects with CPC, CPO, and CPI results, separated by specific crowding paradigm. CPO yields the smallest average ratio, with CPI an intermediate ratio, and CPC having the largest normalized letter height ratio with respect to the isolated character visual paradigm.

4.3 Peripheral Vision for Center Crowded

Figure 4.8 show results for all center crowded, peripheral vision tasks, across center crowding visual paradigms and grouping all subjects together. Figure A.3 shows the control data whereby it can be seen that this not any qualitative difference in the pattern of results between data from internal data, mock sessions, and study sessions.

From these results it can be seen that peripheral vision does appear to get worse, as a function of increased center crowding. However, interestingly, it appears that low levels of central crowding actually enhance peripheral vision abilities such that average normalized threshold letter height actually is able to be smaller for central crowded, as compared to isolated character visual paradigm. At any rate, in all cases, none of these results are statistically significant.

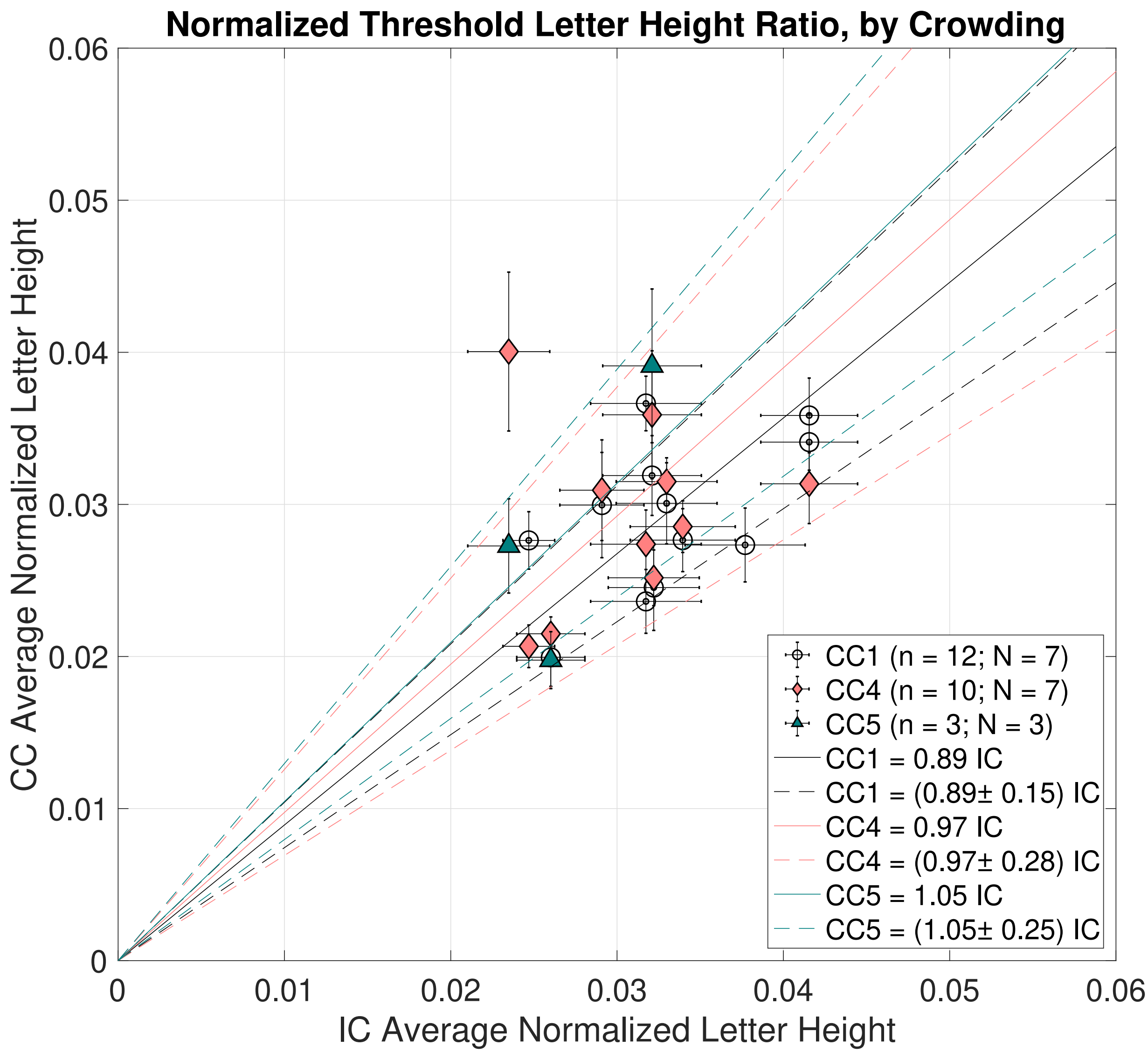


Figure 4.8: **Normalized threshold letter height ratios, comparing CC1, CC4 and CC5 trials.** This plot shows normalized threshold letter height ratios across all subject CC1, CC4, and CC5, separated by the crowding paradigm. On average, increase in center crowding caused an increase in normalized threshold letter height ratio, compared to isolated character normalized threshold letter height. Interestingly, these results suggest that center crowding may help with peripheral viewing in covert attention. None of these differences are statistically significant at this population level.

4.4 Peripheral confusions modeled by visual attention vector overshoot

By simulating the physical activation of neurons on the primary visual cortex, we are able to replicate letter confusions found in prior literature. Specifically, we modeled representation of what the lowercase letters "v" and "w" look like on V1 depending on whether they are correctly centered on the fovea, or off-centered, as predicted by incorrect mapping of the attention vector in peripheral vision where the text is too small or the field is too crowded. Specifically, by using the model that the attention vector overshoots the object and therefore bring the object back to an off-centered location, we match the findings that the letter "v" is represented by the same neuron activation on one brain hemisphere, that the letter "w" would active when correctly centered on the fovea.

The simulation assumes that prior training on the letter recognition has occurred in the case of the centered letter, and as such the semantic stored memory is activated from the representation of the centered letter. In this case of applying the incorrect (overshoot of) the attention vector for viewing the letter "v" in periphery, then one of the brain hemispheres would send perfect match of the centered letter "w" to higher level visual brain structures, while the other hemisphere would send no signal. This would support the notion that, while there would be less confidence from the participant in their response, there would still be greater likelihood to confuse the letter "v" with the letter "w", as opposed to either correctly identifying the letter, or seeing no possible match whatsoever. A possible analogy for the reader would be to focus on a letter "w", physically cover half of the letter, and then reason that one could still perceive the letter "w" by seeing that half is covered and still focusing on the "would-be" center of the full image.

In the contrasting case where the letter "w" is in the periphery, our simulations also show that one is not able to recover the same neuronal activation as "v," regardless of how mis-aligned the attention vector. The reason for this stems from the additional complexity the letter, which creates additional and unique neuronal activation pattern on V1. The combination of these simulations support the one-way confusion of perceiving “v” in the periphery as “w,” coined a “doubling” phenomenon in the prior literature. These simulations of confusing “v” for “w” also explain the “n” to “m” confusions in the literature, whereby the offset of “n” from our attentional vector creates identical representation as “m” on one hemisphere of our visual cortex.

As a last proof of principle, we use the model to show that there is evidence for the attentional vector overshoot, as opposed to an under-shoot, or random probability between overshooting versus undershooting. In the previous cases, the letters showed a symmetry, where either an over-shoot or an undershoot would produce the same effect, and the effect would be independent of whether the letter were presented in the left or right visual peripheral visual field. Other prior literature has documented letter confusions, with more specificity about exactly where in the visual field the letter was presented, and with which eye the confusion occurred. This is useful for us to identify exactly where the attention vector focused, to be able to reproduce such peripheral visual confusions.

Specifically in the case of peripheral visual stimulus shown in the left visual field to the right eye (the left eye is closed/covered), past results show that there are letter confusions between uppercase “B” and “E” that are not present when the stimulus is shown in the center of the visual field.

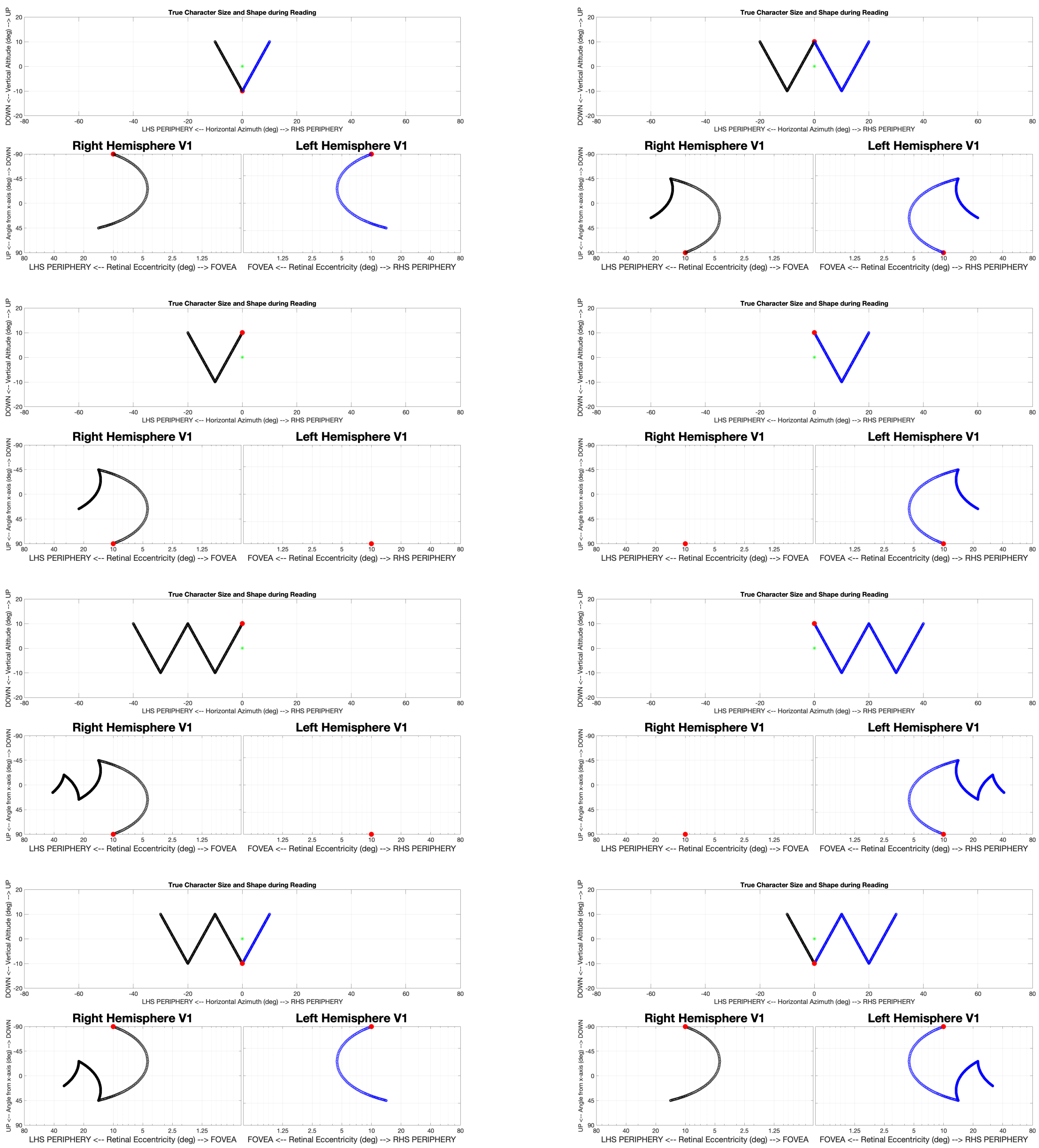


Figure 4.9: **Peripheral letter confusions, "v" and "w". Top left.** V1 neuronal activation when "v" is centered by the attention vector. **Top right.** Same alignment, for the letter "w." **Upper middle left/right.** When "v" is incorrectly centered, with an attentional undershoot or overshoot. **Lower middle left/right.** When "W" is off-centered it looks even more complicated on V1, and could not be confused for "v." **Bottom left/right.** Even if "w" is slightly shifted off-center, even though it produces identical pattern of "v" on one V1 hemisphere, it creates additional complexity on the other hemisphere that would reduce probability for a conscious semantic matching in higher brain structures.

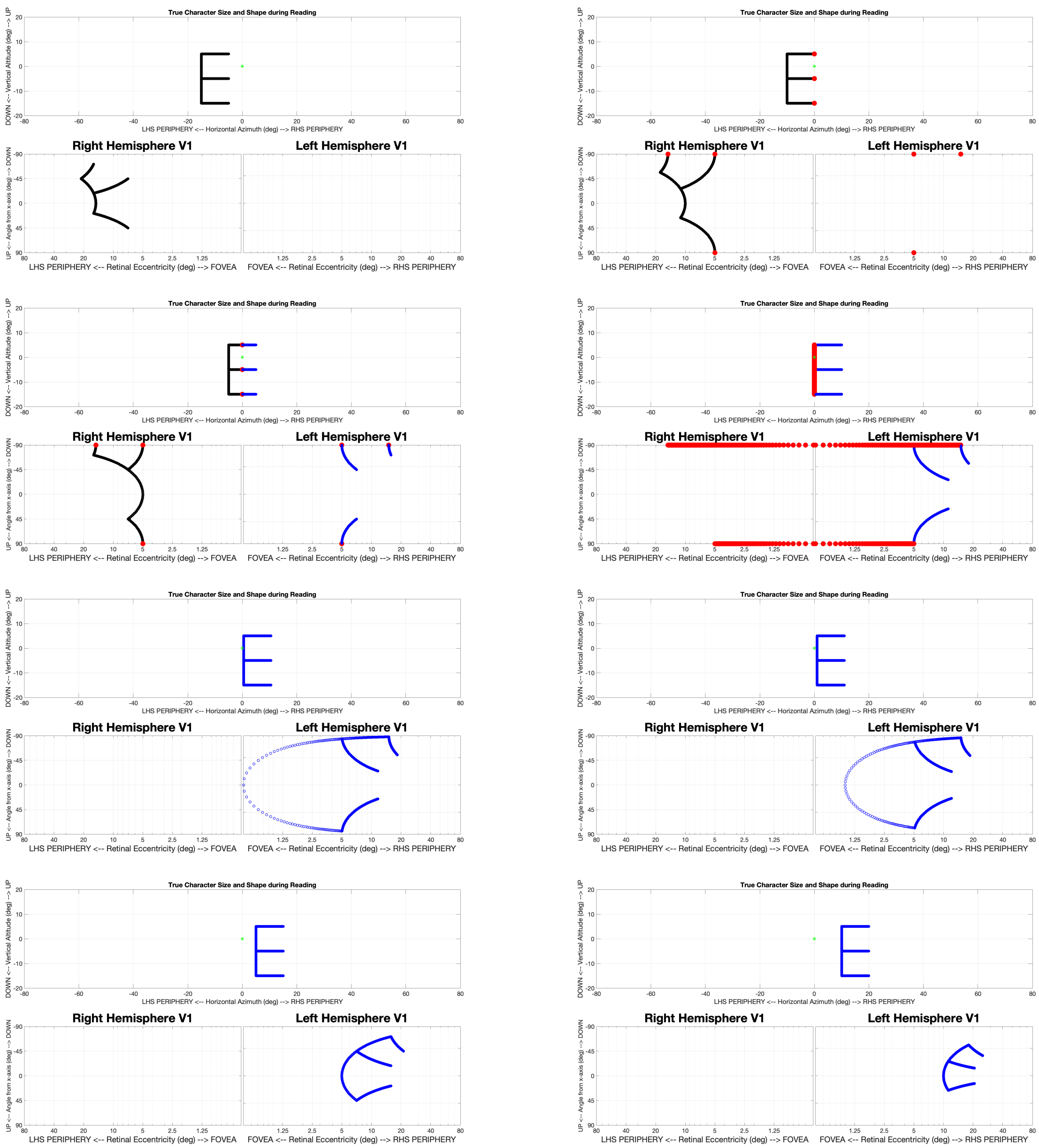


Figure 4.10: **V1 Model, letter "E" translation.** The letter "E" is simulated on the primary visual cortex. The images from top to bottom show the neuronal pattern on the two hemispheres of V1 as the "E" moves across the visual field. These figures also show the resultant pattern on the V1 cortex, when the attention vector fails to target the correct center of the latter. For example, the letter "E" could be anywhere in the visual field, and these images then represent the brain's internal representation, after the vision attention vector has been applied to translate the object to the center on the location of the covert attention.

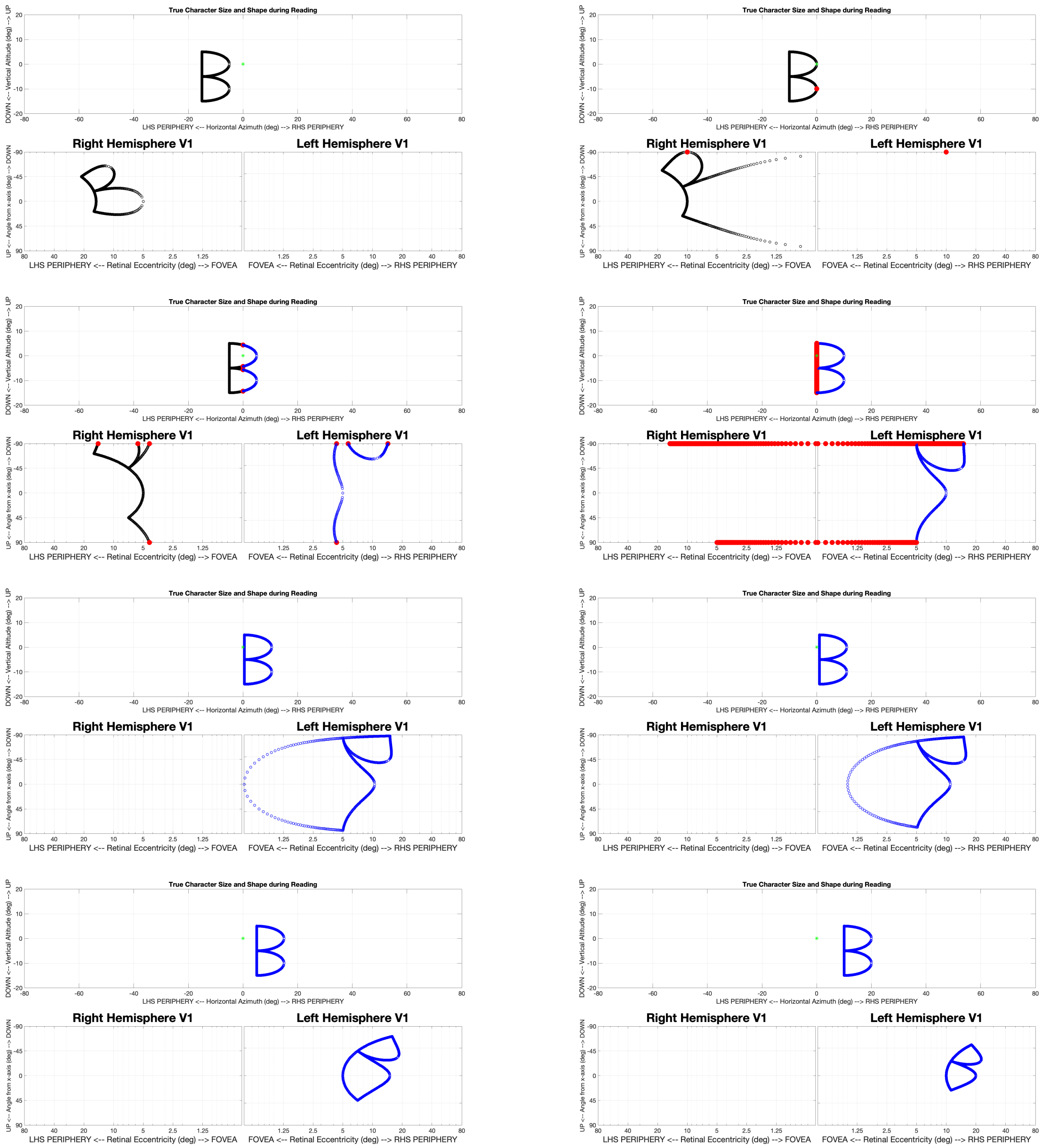


Figure 4.11: **V1 Model, letter "B" translation.** The letter "B" is simulated on the primary visual cortex. The images from top to bottom show the neuronal pattern on the two hemispheres of V1 as the "B" moves across the visual field. These figures also show the resultant pattern on the V1 cortex, when the attention vector fails to target the correct center of the latter. For example, the letter "B" could be anywhere in the visual field, and these images then represent the brain's internal representation, after the vision attention vector has been applied to translate the object to the center on the location of the covert attention.

CHAPTER 5

Discussion

It would make sense that the brain has more than one internal mechanism to make sense of the visual field, depending on where the attention is, and whether we are, in that moment, using covert attention or overt attention to extract semantic representation about our world.

Both simulation and experimental crowding results provide support for the role of a vision attention vector that tries to identify the target object, but that can overshoot, when the peripheral target is too small, or the the peripheral environment is too crowded.

5.1 Comparison of Visual Crowding Level

5.1.1 Dependence on Crowding

The fully crowded peripheral vision was significantly worse than the peripheral crowded peripheral vision, suggesting that there are additional effects than just the receptive field theory, along that are responsible for our ability to extract semantic meaning from objects in our peripheral vision.

5.1.2 Outer versus Inner Peripheral Vision Experiments

Additionally, in the few data points that we have, the innermost peripheral object, which receptive field theory would have predicted to yield best visual acuity, actually yield worst visual acuity, compared to tasks to identify the center (most crowded object), and peripheral object (most far away object). The fact that the outer peripheral object recognition task outperformed both the crowded center task and the target object inner task, suggests that the peripheral vision mechanism performs more accurately when extracting information from the outer edge of a cluster of objects. Such results are in alignment with our vision attention vector theory.

5.1.3 Central Crowding

Interestingly, we show that when the distracting information is in a region of space that is explicitly not connected to the area of our attention, then this additional information may possible allow for improvements to our peripheral vision. This results does offer support for an active attention mechanism, but it is also surprising because normally one would predict that additional visual information would only distract attention away from a peripheral region of interest. It is also possible that these results are just noise, and that there is no effect. Given that our experiment paradigm allowed ample time for participants to scan their attention over the entire visual field (while keeping their eyes fixated on the screen), it makes sense that extra distracting objects in a different region of space would not affect one's ability to identify target information. As long as there is enough time for the brain to shift covert attention over different regions of space, then the brain could perform the internal visual representation coordinate shifts as many times as needed, to search the visual field without moving the eyes. In the case of when the letter clusters are in the middle of the screen, it may be possible for the brain to shift between overt attention, and covert attention. In the case of over attention, where the eyes are looking at the location of attention, the brain is able to use the standard V1 pathway to exploit the innate invariance of the log polar coordinate system. Then, when the attention shifts to covert attention, the brain utilizes its internal remapping mechanism.

5.1.4 1D Fully Crowded versus 2D Fully Crowded

We also have results to suggest that 1D Fully Crowded has slightly better peripheral vision that 2D Fully Crowded. We will need to follow up on greater statistics to be sure. Additionally, the 1D Crowded may impact peripheral visions so much because the crowding dimension is along the orientation of the attention vector. One way to test this is to test another protocol where the 1D Fully Crowded is in an orthogonal direction to the orientation of the attention vector. Such asymmetry, if observed, would provide additional support for the presence of an active mechanism that is operating on top of the passive constraints imposed by low peripheral spatial resolution.

5.2 Insights from V1 log polar model

Even though we do not have a large enough sample size to show statistical significance with our peripheral inner target versus peripheral outer target experiment results, we also gain confidence in our theory from our simulations replicating past experimental findings involving letter confusions in peripheral viewing conditions. Firstly, the fact that we are able to model the "doubling" phenomenon where letter "v" in the periphery is perceived as "w," but that "w," in the periphery is not perceived as "v" supports the notion that the brain attempts to internally shift the peripheral object into a coordinate space where the "attention" vector becomes the origin. In the case of eyesight limit in peripheral conditions, such results support the theory that the brain's attention vector is not able to accurately find the normal center of the object, or the correct location in the visual space. When there is an incorrect mapping, then the incorrectly mapped letter can look quite similar to a different letter, causing a confusion.

Lastly, our simulations involving the specific letter confusions of "E" and "B" show very strong support for the vision attention vector overshoot. Given the fact that the experiment being modeled is for the right eye, with the target object shown in the left visual field, such letter confusions strongly point to the error arising from the "center" of the letter being too far to the left, of both the "E" and the "B." If there were an undershoot, and the attention vector were to land to the right of the letters, then the internal transformation would shift the letters such that the "center" would be to the right of the letters, and then the letters would look considerably different on V1. Moreover, E and B are not generally confused, in the case where they are in center gaze with overt attention. This make sense, from our model, because, for a variety of central perspectives, the two letters look very different in their V1 representation. It is only in the case when one looks to the left of the letters, or exactly on the left vertical border of the letter, that they two letters look similar on V1, and there could be grounds for confusion of semantic information between them.

5.3 Further Elaboration on Arisaka Vision Model

Given that we have support for the notion that there is a top-down involvement of an attention mechanism in human peripheral vision, we explore possible pathways in the brain, by which visual parallel processing might be able to produce and synchronize the various internal coordinate transformations necessary for our model. We offer possible visual mechanisms that start at the retina, moving either directly to pulvinar nucleus (PN) or superior colliculus (SC), or do so after relaying through the LGN. It is established that these evolutionarily older structures have more a more cartesian and linear retinotopic map, and that they are already intricately involved in attention pathways for covert and overt attention.

As visual information travels through the traditional pathway of retina, through LGN to V1, we propose that there is simultaneously, or even in an earlier timescale, a previously establish attention vector that is maintained by PN or SC. In the case where the attention is focused on a peripheral location, as in the case of covert attention, we propose that it is the dorsal stream in the vision pathway which plays the dominant role in processing the visual information. Instead of using information from V1 to V4, as is in the case with processing semantic information that is centrally located, we propose that dorsal pathway information from V1 to MT is utilized within the brain, and that the visual representation, with linear and cartesian coordinate system in MT, is compared with the visual representation in the parallel attention visual processing through PN or SC. As the visual information moves from MT to MST to LIP (as it is known to do from literature findings), we propose that the vision attention vector information is combined with the information from MST, such that, in LIP, there is the internal translational coordinate shift that changes the signal such that LIP is able to uptake the visual information, with the internal attention-based coordinate transformation. At this point, it is known within the visual system, LIP continues onwards in its higher-level semantic visual processing, and the higher level visual processing pathways recognize the semantic information that corresponds to signal that matches previous exposure, training, and reward pathways. Figure 5.2 provides a visual representation of this process.

This “cross-over” from traditional ventral visual pathway, to utilize aspects of the dorsal visual pathway, to then come back to higher level ventral pathway, is a novel proposition. We reason that this make sense however, given our constrains that the internal coordinate shifts within the brain must occur in a cartesian coordinate system, otherwise the attention vector will not able to correctly center the visual representation. Additionally, there is already much work done in neuroscience to support the idea that many parallel processing mechanisms are simultaneously occurring in the brain, and that there are internal time keeping devices in the brain, like the thalamus or the hippocampus, that use synchronization of large populations of neurons as “brain waves” that can force coincidence of events in different pathways to meet up and converge at the same time in a later location.

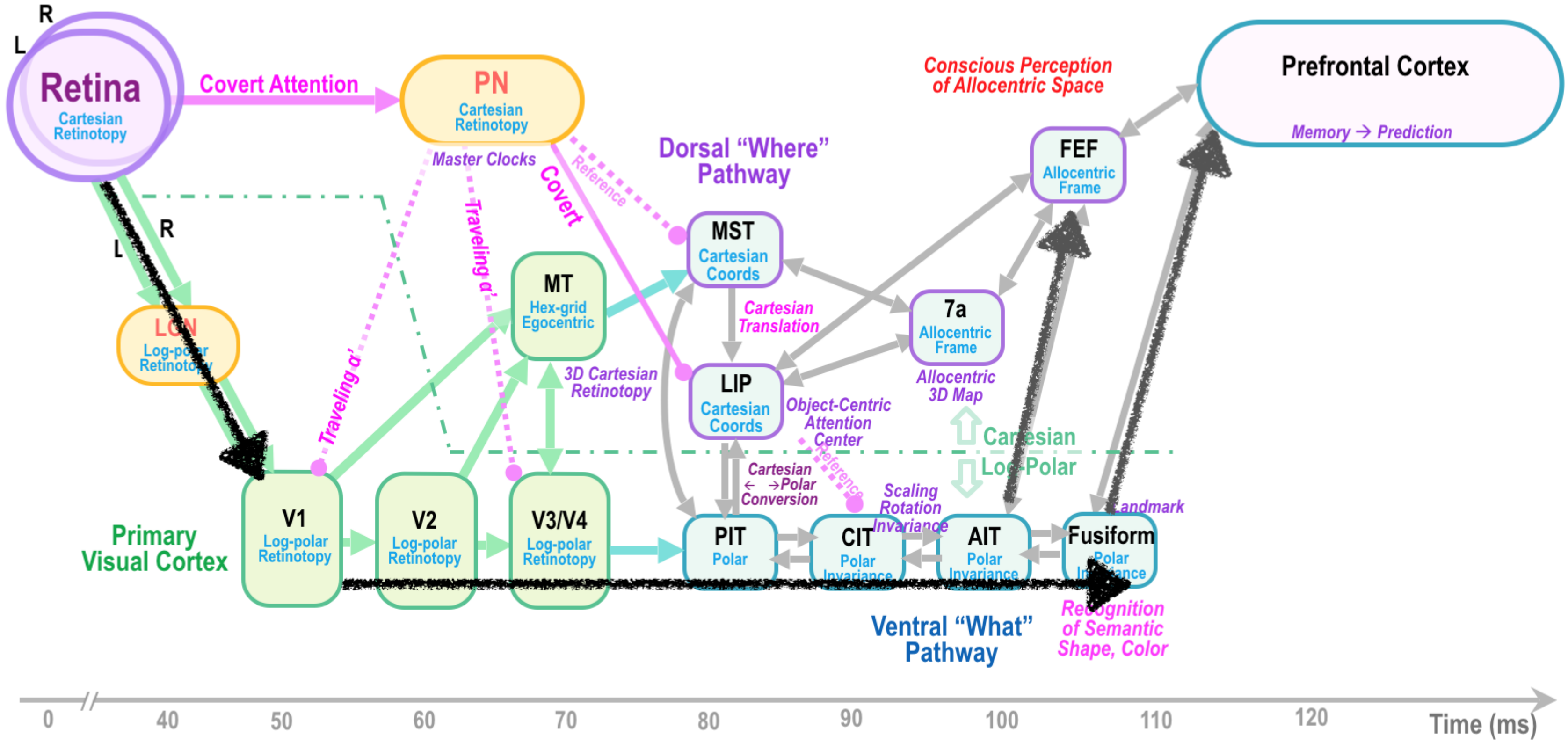


Figure 5.1: **Arisaka Model for Central Vision, Diagram.** This diagram traces the neuron connections in the brain that relay semantic information from center visual field to stored semantic memory in the higher levels of the ventral visual pathway. Adapted from Arisaka (prep).

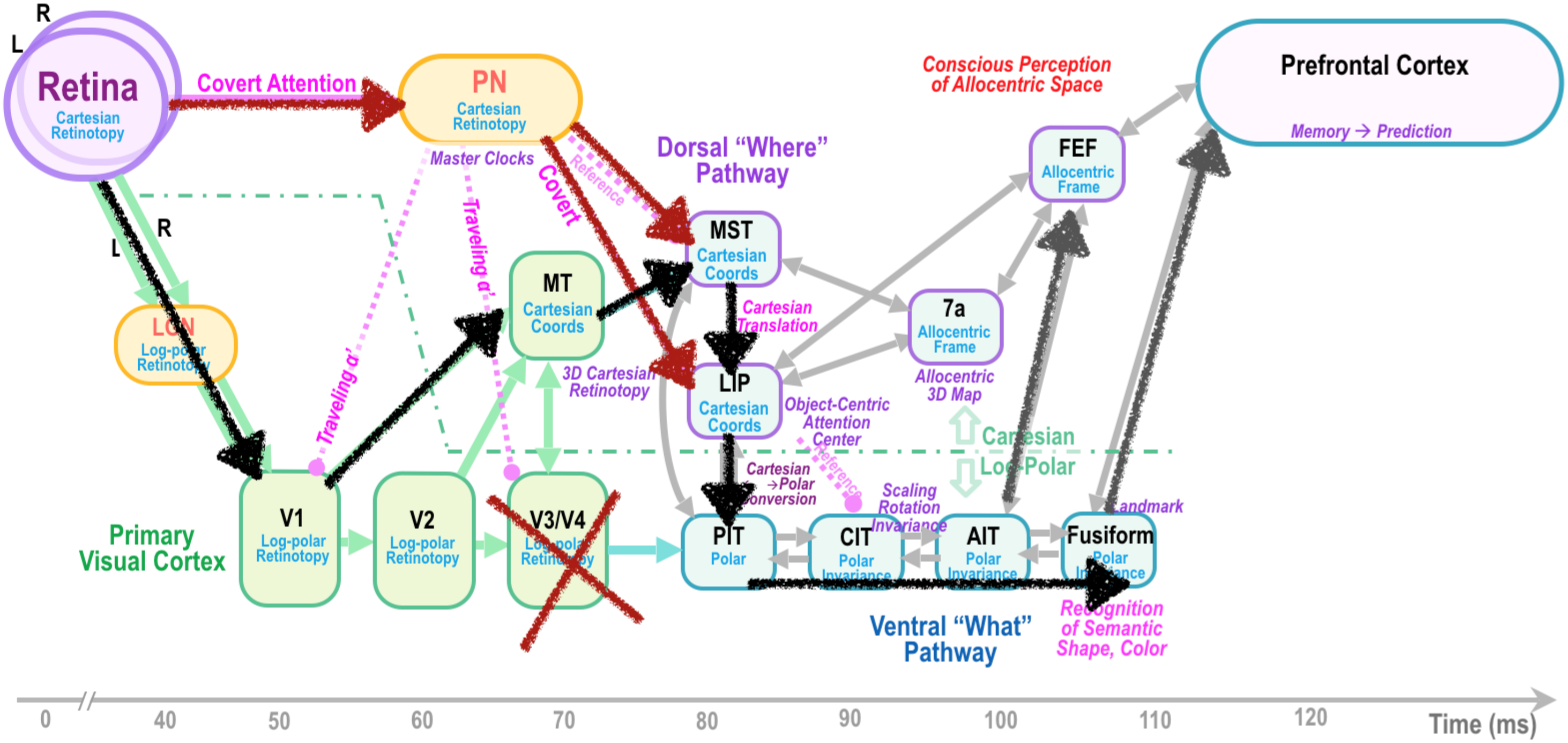


Figure 5.2: **Arisaka Model for Peripheral Vision, Diagram.** This diagram traces the neuron connections in the brain that relay semantic information from peripheral visual field to stored semantic memory in the higher levels of the ventral visual pathway. Because the visual representation is off-center in the case of peripheral visions, a parallel pathway involving encoding of an attention vector by the Pulvinar Nucleus is able to supply the needed information to induce an internal coordinate shift (back to center) inside of the brain. Adapted from Arisaka (prep).

5.4 Caveats and Considerations

Unfortunately, due to COVID19 precautions, we were not able to perform the complete set of study sessions originally planned, for the comprehensive external analysis of how different visual crowding paradigms impact visual acuity for a range of external and unbiased subjects. Given this constraint, the data compiled, analyzed, and presented here includes, in addition to results from external participant recruitment, internal (pilot) data that was collected to confirm experimental setup/design viability or as a an internal mock session, to train Arisaka Lab personnel for role as study session coordinators with external participants.

As a silver lining, the results obtained from internal lab testing, internal mock sessions, and external participant recruitment study sessions are all in general agreement to support our experimental claims. It is important to note that there are reports in the literature that training in visually crowded environments can yield drastically improved visual acuity results (Chung, 2007). However, our results suggest that neither our internal practice (pilot data), nor our mock session results contributed substantial opportunity for task training, and, even if there were small training improvements as a function of time, the stark differences in visual acuity across crowding paradigms was sufficiently preserved to support our scientific hypothesis and research claims.

At the same time, we acknowledge that our research results, are not statistically significant, in single-subject comparisons within the same category of visual stimulus. For example, while fully crowded paradigms are statistically showing worse peripheral vision, as compared to peripheral crowded paradigms, there is not significance that the 1D fully crowded paradigm had any better visual acuity than the 2D fully crowded visual paradigm. Additionally, while we had many examples of varying size for peripheral crowding, it is important to note that we did not see significant differences in visual acuity depending on the size of the peripheral crowding. This does go against our attention vector theory, which would suggest that the larger peripheral box would create more difficulty for the visual attention vector to settle on an attention vector near the target location. At the same time, we acknowledge that we do not have large statistics to compare different peripheral crowded paradigms where the center letter was entirely crowed. It makes perfect sense that the peripheral crowded with the cross geometry would have better peripheral vision results than the same peripheral crowded character with a complete box around it. Naturally, adding more crowding would only make ti worse. We have plans to take additional control measures and acquire additional subject data, when we are able to resume our visual acuity study sessions.

Lastly, and most importantly we acknowledge that we did not have any eye-tracking mechanism, so we did not know exactly where our subjects were looking, for the entire duration of the experiment. Our research results rely on the assumption that our subjects maintained their gaze at the center of the screen. However, it is well established in the literature, that many eye motions happen unconsciously. This means that even, in the optimal scenario that our subjects were honest, and confident that they maintained their gaze in the center of the screen, there is still good change that their eyes may have been moving on the screen without their even knowing it. It is highly probable that random eye movements, and eye movements possible triggered by the onset of the stimulus, could have contributed to noise on our results. They also could have possibly even skewed our research results. We will be able to be much more confident about the validity and interpretation of our research results, if we are able to control for the subject gaze vector and eye motion.

CHAPTER 6

Conclusions and Future Direction

6.1 Manuscript

In the short term, as we work remotely during the COVID-19 crisis, we are writing up our Peripheral Vision Visual Acuity Manuscript, and cross-checking all of our experimental results, with stimulations, and the Arisaka Theory for Physics of Brain and Behavior.

6.2 Visual Acuity Experimental Data

At the same time, are designing future experimental controls and tests, that we can perhaps test on ourselves as pilot data, later on in the summer. We acknowledge that we need more data points for each crowding paradigm, and we are going to focus more specifically on the outer peripheral target, compared to the inner peripheral target, in the case of the peripheral crowding paradigm. We hope to quantify exactly how much loss there is in peripheral vision acuity when the object is in the inner part of a block of text, as compared to the outer part of a block of text.

We also will continue to take more tests on the 1D versus 2D fully crowded paradigm, as well as change the orientation of the 1D fully crowded paradigm to a vertical 3-line block of text, as opposed to a horizontal block of text. In this case, we predict that the attention vector will have no problem locating the correct location, since the crowding will be in a region of space that is not aligned with the direction of the visual attention vector. Such an experiment would be yet another way to parse whether peripheral visions relies more heavily on the bottom-up receptive field theory, or our top-down theory of attention.

Additionally, we intend to further characterize the inner versus outer threshold letter height, to see if our original observations were a one-off phenomenon, or if there is possibly systematic or even universal trend for humans to have better peripheral vision for the outer edge of a cluster of peripherally presented letters.

6.3 V1 Log-Polar Simulations

During this time of remote research collaboration, we are especially enthusiastic about our log-polar model. There is opportunity to continue to explore the attention literature, and combine previous visual acuity experiments, and simulate these experiments with our model. We can compare our results to the experimental results, and using the attention literature, continue to place additional constraints on the internal connections in the brain that control the accuracy of our peripheral vision, and the underlying brain structures that are involved in the process.

6.4 Eye-Tracking

In our future rounds of study sessions, it is important that we are able to measure the eye-position and eye-motion of our subjects, to ensure that they are not moving their eyes around on the screen and negating our assumptions of covert attention. Usage of eye-tracking as such a control mechanism would require reasonable eye-tracking localization precisions, down to under 5 degrees, at least. In such a case, we would just be screening to make sure that our subjects were not moving their eyes significantly towards the targets, and in such cases we would focus analysis on experimental results where the target was at least 15 degrees in the periphery.

We also have additional hopes and more long-term plans to increase the precision of our eye-tracking such that we can measure eye motions on the order of half a degree to around two degrees. In this case, we can actually track how each participant chooses to center their gaze on an object that is place in the center of their screen. We propose that different individuals construct their own unique semantic representation of an object by learning to recognize that object with their eye gaze focused at a particular location in the empty space either within or just adjacent to the lines that comprise that object. For example, in the case of the letter P, we predict that different humans would make eye motions that center the object uniquely on their primary visual cortex. As is demonstrated in the appendix, some humans would focus their gaze exactly in the middle of the "P," and experience their scale-invariant semantic match through that center point, eye gaze alignment. Others would focus their gaze slightly offset from the center of the hole inside the "P," and others might focus their gaze on the vertical line within the form of the "P." Our prediction is that most humans use the empty space within the letter, but that each human has their own preference, and they move their eye, based on their attention vector, to center the object, uniquely for their own semantic object recognition, within their visual cortex. We hope to use eye-tracking to show that different individuals consistently, but uniquely focus their gaze on a particular part a character to recognize the object and have the greatest probability to extract semantic information from the object.

6.5 EEG

There may be opportunity to take EEG measurements, such that we record event related potentials where the clock on the EEG is time-locked to the clock on the stimulus control. If we have exactly the same stimulus, but different tasks (where the covert attention is either on the inner letter or the outer letter), then we might be able to compare differences in brain signal, relating to differences in the attention vector. This would be a far-reaching goal, and would be considered only after we had successfully accomplished all the other aspects on our future goals list.

Part 2

UCLA Improvements for Introductory Physics for Life Sciences (IPLS) Laboratories

CHAPTER 7

Background & Motivation

UCLA Physics and Astronomy Department supports nearly 2000 life sciences students each year, through their undergraduate physics education. Many of these students have never experienced any physics curriculum previously. All of these students enroll for the purpose of achieving not only the curricular requirements for their major, but also their own objectives for the entirety of their physics education. For most life scientists, this three-quarter sequence encompassing mechanics, thermodynamics, fluids, waves, sound optics, electricity, magnetism, and modern physics is their only formal fundamental physics content exposure. As such, these courses leave a very strong impression on UCLA's life scientist pre-professionals. Whatever impact has been made, whether in physics content knowledge, attitudes about physics, or critical thinking and problem-solving skills, remains with these students onwards throughout their life.

Most educators in physics departments are accustomed to the highly symbolic representation of physics, as well as an educational paradigm of repeated exposure to topics, whereby fundamental physics principles are applied in increasingly more complex geometries and general contexts that build from previous conceptual and symbolic exposure. For example calculus is an essential aspect of mechanics and electromagnetism education for physicists and engineers, as it is customary in these disciplines to characterize physical situations in terms the mathematical geometries and constrains. The math allows for both quantitative calculation and also logical proof of consistent physical principles at hand.

However, in the case where students have one single opportunity for physics education, and they are simultaneously studying diverse scientific fields like biology, chemistry, and neurobehavioral sciences, the traditional education of physics ”methods training” does not produce the intended desirable learning outcomes. Instead, life science students become overwhelmed by the combination of new physics concepts with novel mathematical representation, and they struggle to connect the significance of their problem-solving computations to their own education, future career, and real world experience. Life science students have an entire study list of diverse topics, where emphasis in other classes often reinforces memorization and connection of diverse factual information. Students, overwhelmed by a heavy course-load to begin with, are then frustrated to find that their previous study habits and strategies for content organization are not effective for performing well on the activities and assessment in their UCLA physics curriculum. The homework and assessments, are aligned by fundamental physics relationships, from the perspective of the expert physics instructor. However, the students appear incapable, and often unmotivated, to make connections between problem-solving in different categories of physics. The mathematical representation, to them, is divorced from relationships between physical quantities in the problem. And the problems themselves often find solution to engineering-specific constructs, that healthcare professionals, neuroscientists, biochemists, or environmental scientists find unrelated to their fields. As consequence, the students do not learn the physics content, they do not see the relevance or importance of physics in our world, they do not enjoy learning, and they do not improve their critical thinking skills along the way. Instead, they feel confused, frustrated, and utterly defeated from the moment they walk into their physics classroom. They have a pre-existing construct in their mind of what their experience will be like, they experience this for themselves, and then they pass on this information to everyone they know, and recount their challenging physics experience for the rest of their lives.

Instead of having physics a frustrating and traumatically challenging experience for our future world professionals, that perpetrates concepts that physics is inaccessible and confusing for the “average person”, why not adapt how we teach physics to inspire and educate life scientists in topics that are important to them and a larger fraction of humanity? In recent curriculum revisions, universities have focused on modifying physics curriculum to be centered towards the interests and needs of life sciences students, so that they can investigate and apply physics principles to real world and health-related problems that are relevant to our modern day society and healthcare. In the last thirty years, much effort across the country has focused on identifying what particular physics-related learning outcomes are most beneficial for life science students, given the short amount of time physics departments have to work with them, and the considerable breadth of content they are responsible for learning as pre-requisites for their future careers in healthcare and biological sciences.

Overall, physics conceptual learning outcomes appear to be more attainable than physics mathematical problem solving skills, in the short amount of time available to both instructors and students. If physics concepts can be applied to real world situations that students find meaningful, then the students' inherent curiosity and interest in the topic serves as intrinsic motivation to persevere through complex relationships between physical parameters. While mathematical representation of physics parameters as symbols in an equation are necessary to solve for otherwise unknown information, such abstract manipulation does not have inherent value to a non-physicist. First, there must be prior motivation to find the unknown physical parameter in the first place, as well as a conceptual understanding of how the mathematical equation connects to the physical problem and provides the mechanism by which we can find the answer to our questions.

Given that physics problem-solving is a trained skill, and not something that humans are innately programmed to do, it is important to recognize that such critical thinking, problem-solving, and information organizational skills require practice and time for mastery and consistent performance. Given that these skills are necessary to autonomously solve physics problems without excessive hand-holding, it is generally accepted that such skills are desirable outcomes for college physics curriculum. Even other disciplines claim to rely on physics for training in critical thinking, problem-solving and logic, citing that such skills are very important for all professionals in science, technology, and medicine. Even if students are not able to apply calculus to solve electrostatics fields generated from different charge distributions, they are able to learn why different charge distributions create different electric fields, that depend on the specific geometry of the charge distribution. Topics like symmetry, super-position, forces, and energy are able to be reinforced, conceptually, through the different specific cases that they find across mechanics, fluids, electrostatics, and magnetostatics. And students are able to internally reason and problem solve such that they can move through confusion in initial unknowns, to establishing a mechanism that will yield a solution that is based on a logical, and context-dependent relationship between the relevant physical parameters at hand.

As such, reformed content emphasizes connecting physics concepts, using mathematical problem-solving as a tool, only after the physical basis has been characterized and sufficiently motivated. This means that it is very important to connect physics principles to nontraditional physics content. It means that complex, real-world situations will be looked at, and used as motivation to study the simplified physics model that is taught in lower-division undergraduate physics curriculum. Additionally, it means that the physics instructor, who may not be an expert in life-sciences themselves, must learn about what matters to the life sciences student, from the perspective of what physics is important to experts in healthcare and global technology.

Overall, such curricular revisions require an extended team of faculty, staff, and students for successful implementation at R1 research universities, like UCLA. In addition to lecture content and course materials, Introductory Physics for Life Sciences (IPLS) courses often include discussion recitations and laboratory sections. In theory, one would predict that students' exposure to physics via lecture, discussion, laboratory section, and their own independent practice on the homework sets, would reinforce their physics education and motivate students to connect between the theoretical physics relationships in lecture and the practical investigations performed in laboratory. This could, in theory, boost physics learning, mitigate challenges associated with such brief exposure to the content. However, UCLA, along with many other R1 universities across the country, have found that life science students often see no merit to their undergraduate physics laboratory experience. They perceive no relevance in their physics laboratory work to either class content or real world experience.

As such, they feel their time is being wasted, they do not enjoy the activities, and they provide scathing end of quarter course evaluations.

Such consistency of negative student feedback, in conjunction with pressure for UCLA's life sciences division, prompted UCLA Physics and Astronomy Department to re-evaluate its IPLS education curriculum, and specifically revise its laboratory curriculum and pedagogy to better achieve specific desired student outcomes. In the context of IPLS laboratory revisions, this meant creating these desired outcomes, assessing the current state of the laboratory experience, and modifying various aspects of laboratory pedagogy, materials, and structure, to better align with achieving our physics outcomes. While the recitations are often coordinated by the instructor in conjunction with a Graduate Teaching Assistant (TA), the laboratory sections are often a separate curriculum that is autonomously taught by an independent TA, who may not be in any way connected with the lecture course content. At the same time, this laboratory sections is worth a considerable fraction of the students' overall physics course grade (15% at UCLA), so students are understandably inclined to relate their laboratory experience to their lecture physics learning outcomes. Since TAs have historically acted as the instructor for UCLA IPLS laboratories, such revisions relied heavily on graduate student student insights about logistical constraints, laboratory content, and student experience. Useful elements of the laboratory could be preserved, and effort could be placed on changing those aspects which were actively taking away from achieving the desirable outcomes.

Figure 7.1 shows specific examples of UCLA IPLS laboratory student course evaluation feedback, that was used to help guide the first step of revisions. In general, students commented on how they did not learn anything from the labs, how the equipment was confusing or did not work like it was supposed to, the lab material did not relate to their physics lecture course content, and the laboratory manuals were to rigid to be able to learn anything. Additionally, students would even go so far as to thank their TA for *trying* to make the most out of the lab. If even the most competent and hard-working TAs were unable to make the laboratories useful the students, then one can only presume that student were suffering even more egregiously with TAs who were not as pedagogically experienced. Lastly, students even proposed that the laboratories could be made to better, suggesting that students were in theory supportive of the physics laboratory as possible learning environment, given that the above feedback could be implemented.

*"**I don't feel like the lab helped me learn any physics**, all I learned was how to use Data studio. . . I usually hadn't covered the lab topic in class before and didn't always know what was going on."*

*". . . **preset assignments for the lab are not very helpful for learning** and unnecessarily long."*

*"**The labs did not relate to what we were learning in the class** making it hard to follow the concepts."*

*"**The TA did a great job in merging the lab with the course material** even though the course material was vastly different from what we were doing in lab. **The lab itself was frustrating** because the equipment was not doing what it was supposed to do most of the time."*

*". . . **overall lab experience was very unhelpful to me**. We would work on labs that were very confusing to understand and to make thing worse we had to use Data studio which would always cause technical problems. **I believe this lab can be amended to make it more useful and relevant to the students**."*

Figure 7.1: **Pre-revised lab course evaluation feedback, 6AL.** Example verbatim quotations from students during end of quarter course evaluation feedback, regarding the introductory mechanics laboratory, Physics 6AL, before revisions.

CHAPTER 8

Laboratory Design

8.1 Student Learning Outcomes

The three main learning outcomes for students in the IPLS labs were that student would build conceptual understanding of real world physics, improve upon their critical thinking and problem solving abilities, and feel increased enjoyment around or at least appreciation for physics as applied to human health and technology.

UCLA IPLS laboratories had been operating, for the last 30 years, as a single-credit, two hours per week, registrar-scheduled meeting, whereby in ten groups of three, students measure physical properties about a system that relates to what they are learning about in class. Based on prior student feedback that recommended for the labs to be more relevant to the course content, we constructed the labs on the primary objective to reinforce conceptual physics principles in real world applications that were relevant to what students were learning about in their lecture course. The overall physics course revisions standardized a textbook across all UCLA IPLS lecture sections, that emphasized conceptual physics applied to real world problems. Each laboratory was designed to connect to at least some aspect of the assigned physics textbook, so that students had a resource to tangibly connect what they were learning about in laboratory to their lecture content.

In the the revised laboratories, emphasis was shifted away from mathematically quantifying measurement uncertainty and error propagation, and emphasis was shifted towards increasing student problem solving skills and critical thinking autonomy. In many cases, labs were designed for students to ask their own scientific questions, make their own predictions, and build their own experimental setup to compare their measurements to their theoretical physics predictions. Additionally, laboratory equipment and protocols were designed to engage students interest and enthusiasm for physics, by focusing many laboratories on using humans as subjects for part of the experiment, or using technologically relevant equipment that students would identify as being relevant to their own life. Lastly, laboratory manuals were re-written such that students were no longer told, step-by-step what actions to take to make their measurements. Instead, pre-laboratory assignments reviewed relevant course content in a "flipped-classroom" approach to learning, and laboratory manuals outlined the laboratory main idea, available materials, and images of what the completed setup looked like. Sometimes, students were told what physical parameter they were trying to quantify through their experiment, and other times, it was up to the students to review their pre-laboratory materials and decide what they wanted to set up, and what they wanted to measure, using predictions about how physical parameters were related in their physical apparatus.

To support this student-centered, critical thinking-based approach to physics laboratory exploration, Undergraduate Learning Assistants (LAs) were introduced across all the IPLS lab sections. LAs, through UCLA CEILS (Center for Education, Innovation, and Learning in Sciences) Learning Assistant Program. Both GTAs and ULAs were mentored to work together, as content and pedagogy experts, respectively, to support student physics conceptual understanding, problem-solving, and active critical thinking in constructive group dynamics during laboratory sections.

Additionally, UCLA IPLS Laboratory resources were modernized and centralized such that all students had access to the same laboratory syllabus, revised laboratory manuals, and online content resources to support them through their laboratory course. Pre-labs, attendance, and in-laboratory assignment were all worth credit, such that the lab grade would reflect a combination of student effort conceptual understanding, over the course of the quarter.

Lastly, Pre and Post Quarter assessment surveys were incorporated into the course grading structure, such that students had a (small) incentive to answer questions about their prior physics content knowledge and attitudes about physics before starting their first laboratory and again answering the same questions at the end of the quarter. Results from these surveys provide some insight into whether these laboratory revisions are meeting our desired student outcomes. We have assessment data on laboratories from before the revisions, and, now, over two years of data on UCLA IPLS laboratory student learning and attitude gains, post revisions.

8.2 Pre and Post Quarter Surveys

Both physics concept surveys and physics attitude survey were administered to students, at the start of the quarter and the end of the quarter. Depending on the particular laboratory course topics, students took a concept inventory that was specific to that physics topic. For example, in the first quarter of IPLS laboratory, students studied introductory mechanics, and so their concept inventory used the Forces Concept Inventory, which is nationally recognized standardized assessment for measuring student physics conceptual gains in introductory mechanics. Similar diagnostics were administered in thermodynamics and electricity/magnetism, for the other two quarters of laboratory. These concept inventories were integrated into the laboratory sections such that 30 minutes of the first lab and 30 minutes of the last lab of the quarter were used for in-person, supervised, completion of these assessments. These concept inventory results provide inside into a holistic perspective on student content learning gains through the entirety of our physics series revisions. As the course format and laboratory format were changed together, these physics concepts diagnostic data are most useful to asses how particular aspects of different instruction in the lecture or discussion sections affected student learning gains.

To assess unique impact that the laboratories had on students perceptions of physics, we administered pre and post quarter physics attitude surveys, C-LASS, and E-CLASS, to all students in every laboratory section, via an online google form. Students had a week-long interval of time at the beginning of the quarter to complete their PreQ survey for a small amount of course credit, and students had a week-long interval time of time in the last week of the quarter to complete their PostQ survey for a small amount of course credit. While the C-LASS measured overall attitudes about physics problem-solving (which probed comprehensive attitude shifts lumping both lecture and lab), the E-CLASS survey framed the questions regarding attitude and beliefs about physics in the context of experimental context. Questions asked about designing experiments, following instructions, and troubleshooting when equipment was malfunctioning or results were different than expected (Wilcox and Lewandowski, 2016).

For UCLA physics department assessment of curricular improvements and insights into physics education research interventions, we worked closely with UCLA's Center for Advancement of Teaching (CAT), formerly known as Office of Instructional Development (OID) to construct an inclusive and comprehensive IRB for all UCLA IPLS course products, which includes information about their pre/post quarter attitude surveys, as well as their registrar data, as long as all information is anonymized before presenting to any audience not explicitly granted approval within the IRB documentation. All assessment and data analysis methods were approved by University of California, Los Angeles Institutional Review Board IRB#19-000578.

8.3 Student Laboratory Experience

Nearly every UCLA IPLS laboratory activity was either significantly modified or completely scrapped to create a more hands-on exploration with modern technology and human involvement. Many labs had measurement apparatus that produced data-points on a computer without the student understanding how the measurement was even taken in the first place. Even though these detectors could be very accurate they did not help students meet the learning outcomes of understanding the fundamental physical principles at hand in the experiments. For example, we swapped the sonar velocity detector for a physical camera with open-source tracking software, so that students would be forced to take position data and compute the velocity results from first principles of frame-rate and displacement of a target from one frame to the next.

Given that some fundamental physics content require simple systems, like oscillations in springs and pendulums, we designed some labs to be more straight-forward, and perhaps less interesting from a life sciences perspective. In these labs with basic physics principles, even though students may have a less exciting time, they would be able to develop and apply important skills, like creating their own scientific question, creating their own hypothesis, and take measurements in the experiment setup from their own choice of particular experimental parameter comparisons.

In this way, we were able to re-purpose much pre-existing UCLA physics department lower division laboratory equipment, and focus funding to purchase equipment specifically relating to life-sciences applications or modern, real-world phenomenon. Overall, we interweaved labs testing fundamental physics models with labs that explored a more complicated, but biologically relevant phenomenon with aspects that could be explained and better understood through fundamental physics phenomenon.

Secondly, we re-wrote nearly every single UCLA IPLS laboratory manual, such that general background information could be provided that motivated the general problem at hand, and offered some possible mechanisms for investigation. The equipment list was explained, and the general physics topics were reviewed. Then, the students needed to use the equipment to ask their scientific question, make their predictions, set up their experiment, take their measurements, and reflect on their results.

Previously, in the pre-revised laboratory, students were given explicit instructions regarding even what buttons to press in their programs to generate the plot that was their experimental results. With this plot alone, they were able to raise their hand, show their TA, and be checked off for laboratory completion. In the past there had been no accountability for understanding the experimental setup, or reasoning through the physical meaning of the plot results on the computer screen. Therefore, instead of telling students what they needed to plot on their computer screen, the we challenged the students to find the answer to their scientific question, by using their available technology and experimental measurements.

Lastly, to support students after they had performed their experiments and generated their data, we created an online laboratory write-up template, so that students had a repository to record each step of their scientific method thinking process. In this way, the goal shifted from just generating the results, to making sense of the results, articulating the results, and connecting the results back to the original scientific method and the hypothesis. Students then, as a laboratory group, submitted this collaborative online document to their TA for grading. Students were able to bring their laptops to lab and work through this write-up during their lab, such they could record their ideas and document their results, electronically in realtime, modeling how modern experiments are conducted today. Our hope is that such scaffolding supports students to be able to autonomously create their own logical scientific method process and organization structure for communicating their ideas and findings in their future.

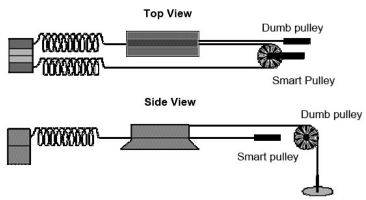
Students were encouraged to bring their own laptops to laboratory section, whereby they could access the laboratory together as a lab group, but on their individual computers, via Google Drive. They could make a copy of the laboratory activity template, save the copy with their own group name, and work together on the document from their individual computers, while discussing the material and performing the experiment together. This allowed students to make the most efficient use of their time together during their 2-hour laboratory. As they had ideas, working together as a group, they could record their data and write up their notes electronically. Most laboratory groups, in this way, would be able to complete their during-laboratory assignment in the 2-hour time frame of the lab. Students were given an additional 48-hours after the end of their laboratory section to submit their final document, in case they wanted to finish polishing any analysis after their lab. They submitted their final "During-laboratory" document, by converting their Google Slides write-up document into a PDF, and uploading their PDF to an online assignment repository called GradeScope. The students could "tag" each other through on submission, so that the single submission, with single pass by the TA would award the credit and provide the laboratory assignment feedback to every student in the group. GradeScope will be further discussed in a future section.

level.

2. Weigh the glider to obtain its mass, and record this value in the "Data" section.

3. Assemble the springs, glider, smart pulley, and thread as shown in the figure below. One spring is attached to a bracket at the end of air track and to one end of the glider. The other end of the glider is attached to a second spring by a thread which passes over the smart pulley. The second spring is then attached to the bracket. The springs should be tensioned so that you can get an end-to-end glider motion over a distance of at least 40 cm without either spring being completely compressed.

4. Mount a dumb pulley (which has low friction, but is not connected to the computer) on the same fixture that holds the smart pulley, albeit in a vertical plane. Using a long piece of thread, connect the mass hanger to the glider. Make sure the thread passes over the dumb pulley so that weights added to the hanger will displace the glider.



PROCEDURE PART 1: MEASURING THE SPRING CONSTANT k

1. Our first task is to measure k, the force constant in $F = -kx$ of a Hooke's Law spring. Call up a blank Excel worksheet and prepare three columns to record the total mass in the hanger (including the mass of the hanger itself) in grams, its weight in newtons, and the position of the glider in meters. In the mass column, type "0" and "10" in the first two cells. Select these two cells, position the cursor at the lower left corner of the bottom cell until it turns into a lopsided square, and drag down the column to fill it with a series up to 60 grams. The running yellow box shows how far the series continues.

2. Fill down the next column with the force values. Remember how to do this? Type "`=A3*9.8/1000`" in the cell next to the mass value of zero, *being sure to use the correct cell designation corresponding to your spreadsheet* (where we typed "`A3`" above, you should type the cell containing the first value in the mass column). Then fill down the forces next to the masses.

3. Now make the measurements. Turn on the air blower, and help the glider come to equilibrium. Add mases to the mass hanger, one at a time, and read the distance (in meters!) from the scale on the air track aligned with one corner of the glider. On your spreadsheet, record the distance corresponding to the addition of each mass in the mass hanger. Be sure that you use values corresponding to the entries in the mass column (including the mass of the hanger itself). If you need to use different masses, change the mass entries; the forces will be

recalculated instantly.

4. When you have filled in the distance column next to the force column, chart these variables against each other in Excel, and find the slope. Here is a reminder of how this is done:
   - Select the cells with numbers in the force and distance columns.
   - In the "Insert" tab menu, select the "Scatter" option without connecting lines. After clicking on this line-less scatter option, the chart should appear.
   - Within the "Design" tab of the "Chart Tools", in the "Chart Layouts" area, click on the left-most (and upper-most) layout option. This will place titles on the chart that you can edit or delete.
   - Create your own title and labels for the axes.
   - In the "Layout" tab of the "Chart Tools", click on "Trendline" in the "Analysis" area. Select "More Trendline Options...". In the pop-up window, make sure "Linear" is selected, and check the box beside "Display Equation on chart". Click on "Close".

Convince yourself that the slope is $1/k$ and not k. Record the value of k in the "Data" section.

PROCEDURE PART 2: PLOTTING ENERGIES

1. Unhook the mass hanger string. Hook up the smart pulley physically and virtually, in Capstone (the sensor is called "Photogate with Pulley"). Choose the "Table & Graph" option in Capstone. Choose "Position (m)" for the y-axis of the graph. Add another graph by clicking the "Add new plot area..." button. On this new graph, select "Linear Speed (m/s)" for the y-axis. Add a third graph and plot "Linear Acceleration (m/s^2) on the y-axis.

2. With the air blower on, pull the glider out, click "Record", let the glider oscillate several times, and click "Stop". The velocity and acceleration graphs resemble the sinusoidal oscillations of a simple harmonic oscillator, but the position graph consists of a series of S-shaped curves increasing in y value. This shape results because the smart pulley does not distinguish between the forward and reverse directions of motion; it merely counts the number of times the spokes block the photosensor and records the result as positive distance. Thus, each S-shaped curve on the position graph is produced as the oscillator moves from one endpoint of its motion to the other.

3. Now record just half of an oscillation. Pull the glider back, click "Record", then release the glider. **Make sure to click "Record" at least a second or two before releasing the glider.** Click "Stop" as soon as you see the glider start to reverse directions, making sure not to stop it too early. Your postion graph should be S-shaped and your velocity graph should look like an upside-down "U".

4. Click "Select Measurement" in the table and choose "Position (m)". Copy the values over to a column in Excel. Next, change the selected measurement in your table to "Linear Speed (m/s)". Copy these values to a different column in Excel.

5. Calculate the kinetic energy as a function of time using your velocity measurements, by setting up a formula in Excel. Recall that the kinetic energy of an object with mass m and speed v is $KE = (1/2)mv^2$. Now plot kinetic energy in Excel. You should get a curve that looks like

Figure 8.1: This figure shows an example two pages of a pre-revised mechanics laboratory manual. Every single instruction is outlined to the student, whereby the student does not need to think about anything themselves. From such language in the manual, the student places more emphasis on performing the tasks, and does not think about why they are performing the experiment in the first place.

Fall 2019 5A Lab 7 Manual
UCLA Department of Physics and Astronomy
Follow Lab 7 Assignment Template (to be completed during lab)
Answer 1-2 phrases/ideas for each part of questions (complete sentences not needed).

Activity 0: Review Your Pre-Lab (can review your pre-lab while you plan Main Lab)
Goal: Use your pre-lab resource and ideas to help you design your Main Lab Activity

Lab Main Activity: Conservation of Energy with Spring-Cart System:
Goal: Design and perform experiment to show how total energy is conserved between kinetic and potential energy in mass-spring system without friction.

Procedural Notes:

1. Review your pre-lab and prepare your experiment for answering the following questions: Is energy conserved between kinetic energy and potential energy in a mass-spring system?

2. You will use PASCO camera and Tracker, so bring up all the resources you have used previously for the camera and Tracker software. You will also use benefit from bringing up the Excel spreadsheets from before that converted your position points into velocity data points.

3. You only need your cart to undergo 2-3 oscillations (bounces back and forth). Be sure to do SMALL oscillations so that the cart does not hit the side of the track and experience a sudden velocity change from an external force of the side-rail. In this lab you are interested in energy transfer within the system without any external agents.

4. You are responsible for converting your position and velocity measurements into potential and kinetic energy measurements. Consult your pre-lab to review helpful problem-solving steps. (If your table does not have a scale, use 250g as the mass of the cart).

5. You are responsible for experimentally determining the mass of your cart and the spring constant for your spring system. There is only one spring constant for your entire spring system. Review your pre-lab for ideas on how to perform these measurements.

5AL During Lab 6 Assignment Prompts: Write-up submitted as a group by table at end of lab.
This write-up is based on Activity 1, after group members have reviewed their pre-lab (for full credit).

Slide 1: Introduction Slide:
- **State** all group member full names, date, lab number and title, and table number

Slide 2: Scientific Question:
- **State** your scientific question that is specific, quantitative, and testable with equipment provided. This page should be a freebie because the scientific questions is given to you in this lab. Feel free to phrase it as quantitatively or interestingly as you would like, as long as you are clear on how you are going to answer your question through your experimental trial and analysis.

Slide 3: Prediction:
- **State** your prediction, as a group that answers the scientific question. Try to be quantitative if possible.

1

Fall 2019 5A Lab 7 Manual
UCLA Department of Physics and Astronomy
Follow Lab 7 Assignment Template (to be completed during lab)
Answer 1-2 phrases/ideas for each part of questions (complete sentences not needed).

Slide 4: Experimental Equipment and Procedures:
- **Describe** equipment required to perform the experiment so that someone unfamiliar would be able to recreate the experiment in a different place and at a later time.

- **Discuss** your mass and spring constant measurements here, as they are part of the experimental procedure for using your raw data in your analysis.

Slide 5: Data Results:
- **Show** raw data experimental results.

Slide 6: Analysis and Conclusions:
- **Describe** any analysis that needed to be performed on the raw data to make sense and answer the scientific question.

- **Show** Google Sheets, Excel plots, or equations of how data is converted into final energy measurements. Show plots of kinetic energy vs. time, potential energy vs. time, and then also the total energy vs. time, all on the same axis (use different colors in Google Sheets).

- **State** a final interpretation of the data results, acknowledging error or uncertainty in the experimental setup or experimental measurement.

Slide 7: Sense-Making: connecting results back to prediction & last week's physics:
- **State** results, answer to the experimental question, and comparison with original predictions, along with the physics model/theory applicable here and how it compares to results.

- **Compare** results in this week with anything you have learned previously about energy, conservation of energy, or energy transfer from one form to another, in a system to surroundings. Connect your experiment back to a real-world example or something that matters to you.

- **State** one idea for experiment error (if you had any), and justify why this error makes sense in the context of how the experiment is set up, the limitations of the measurement device, or additional factors in the experiment that make the physics more complex than the problems that you are learning how to solve exactly in class.

- **State** one physics concept that you were able to apply to this lab from your class, and one concept that you were able to build skills and improve on through working through this activity (something that you learned or got better at).

2

Figure 8.2: This figure shows the entire two-paged lab guide for the revised version of the same conservation of energy lab. Students are given a general outline for the laboratory structure, with emphasis placed on formulating their scientific question, predictions, experimental setup and results for themselves.

8.3.1 Mechanics laboratory activity (5AL)

Students are able to understand both the measurement system as well as the experimental results, when they physically setup their camera, look at their image on the screen, and record their movie. Using first principles from kinematics, they are able to compute velocity and even acceleration information from their raw position vs. time measurements.

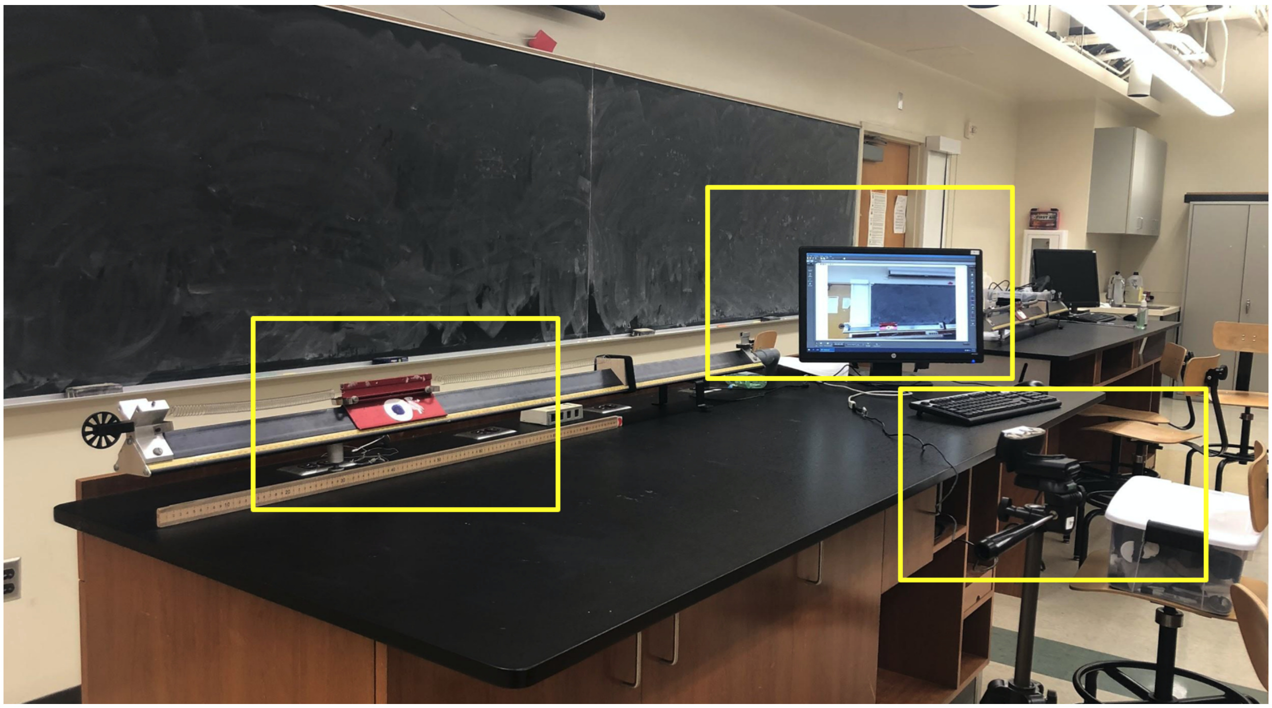


Figure 8.3: This photograph shows an example UCLA IPLS mechanics laboratory setup, whereby students are tracking the motion of a cart on a spring using a physical camera with tracking software.

8.3.2 Fluids laboratory activity (5BL)

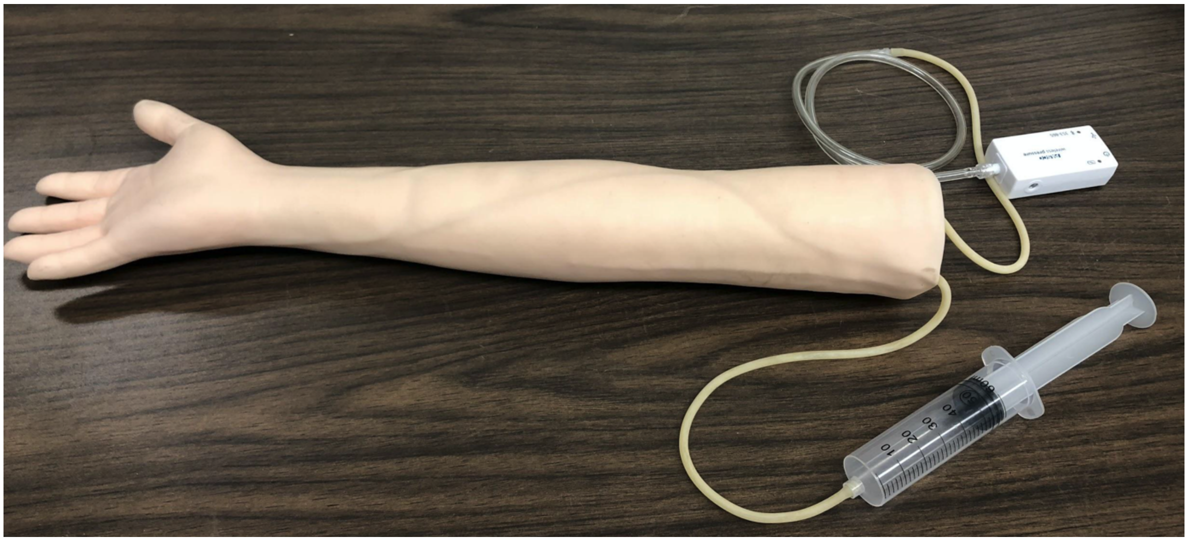


Figure 8.4: This photograph shows an example UCLA IPLS mechanics laboratory setup, whereby students explore pressure changes in a system as they control the volume in the system. The inner gas chamber looks like a human arm, so that students can construct an activity whereby they simulate pressure fluctuations that resemble human blood pressure. While the ideal gas model is not applicable to the fluid-filled human vasculature, such a model can help conceptualize what blood pressure physically is. Students explain the difference between systolic and diastolic pressure within the human body, and define absolute pressure compared to gauge pressure.

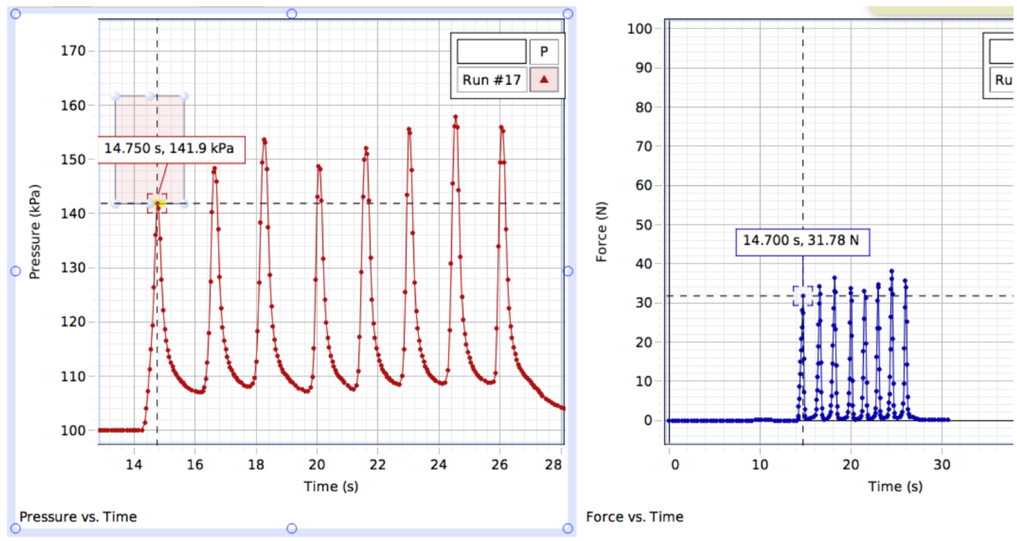


Figure 8.5: This figure shows an example of 5BL mock blood pressure data, from compressing the system of an ideal gas to increase the pressure. When the experimenter regularly compresses and releases the syringe at constant force, the "blood" pressure undergoes oscillations that resemble human blood pressure. Part of the activity was to try to find the force such that one was able to simulate normal human blood pressure. This required students to convert between absolute pressure and gauge pressure in their pressure measurement device, as well as convert between different units of pressure to gain insight into the size scale of the gauge pressure change actually associated with human blood pressure. **Left.** The pressure sensor is wirelessly connected via bluetooth to the computer, so that the student is able to record realtime measurements of pressure as they change the volume in the syringe. **Right.** When a force sensor is used to compress the syringe, the student is able to simultaneously measure pressure and force as a function of time. Since pressure is force per unit area, the hypothesis would be that the pressure changes in the human body are directly related to changes in force within the human body. This helps to build a conceptual understanding of how the physics of fluids, pressure, and volume plays an important role in human blood pressure.

8.3.3 E&M laboratory activity (5CL)

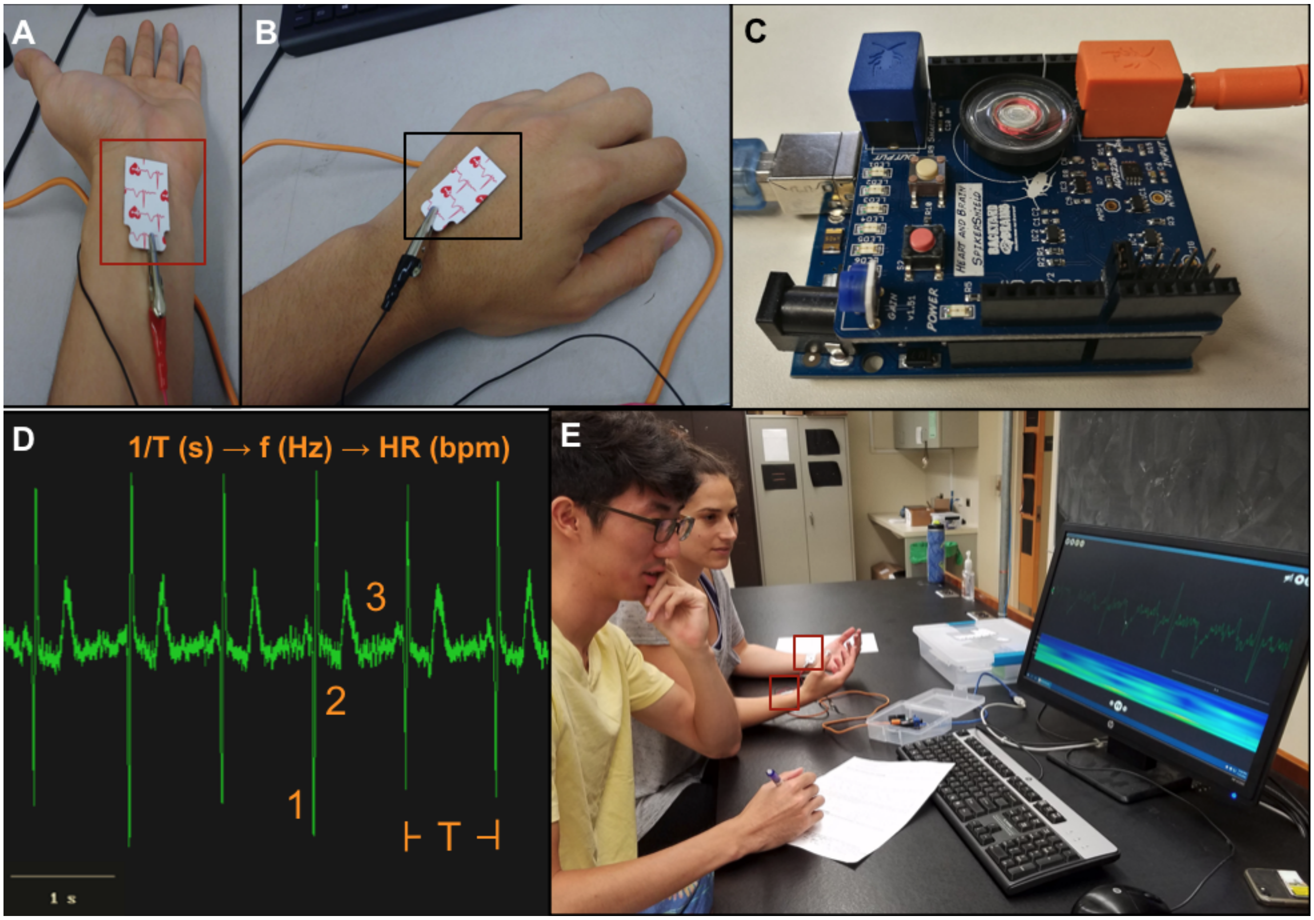


Figure 8.6: **EKG Laboratory experimental setup and data collection.** Students are responsible for setting up the EKG themselves, and measuring electric potential difference across the electrodes as a function of time. **A,B. EKG electrode placement**. Lead I wrist placement with each red lead on inside of wrist and black lead on top of either wrist or hand. **C. Hardware.** Backyard Brains Heart & Brain SpikerShield Arduino, with USB connection and single 3-lead port. **D. Sample Data.** EKG raw data for heart rate calculation and various heart activity timescales. Heart rate (bpm) is calculated via inverse of one full cycle of heart activity. A single period of heart activity shows three distinct shapes, which each correspond to different aspects of cardiac muscle activation during the course of a single heartbeat. **E. Lab Setup.** TAs practice data collection with the laboratory worksheet.

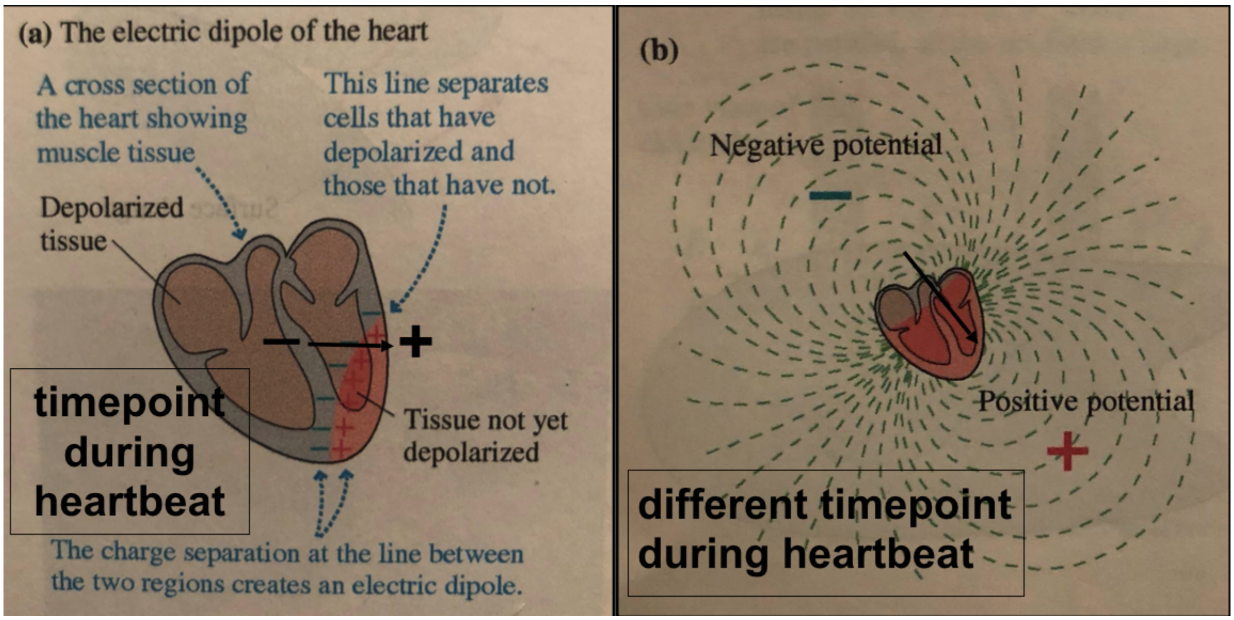


Figure 8.7: **Knight textbook EKG electric potential visualizations. a. Heart modeled as electric dipole.** As cardiac muscle depolarizes during a heartbeat, a wavefront of "charge separation" moves across the heart. **b. Dipole electric potential.** At the interface of depolarized and not-yet-depolarized tissue, there is an effective "current" dipole that creates a dipole electric potential. Through the course of a heartbeat, the dipole orientation and magnitude changes. These changes create the voltage signal observed during EKG recording, though the leads remain in fixed locations. Adapted from Knight et al. (2013).

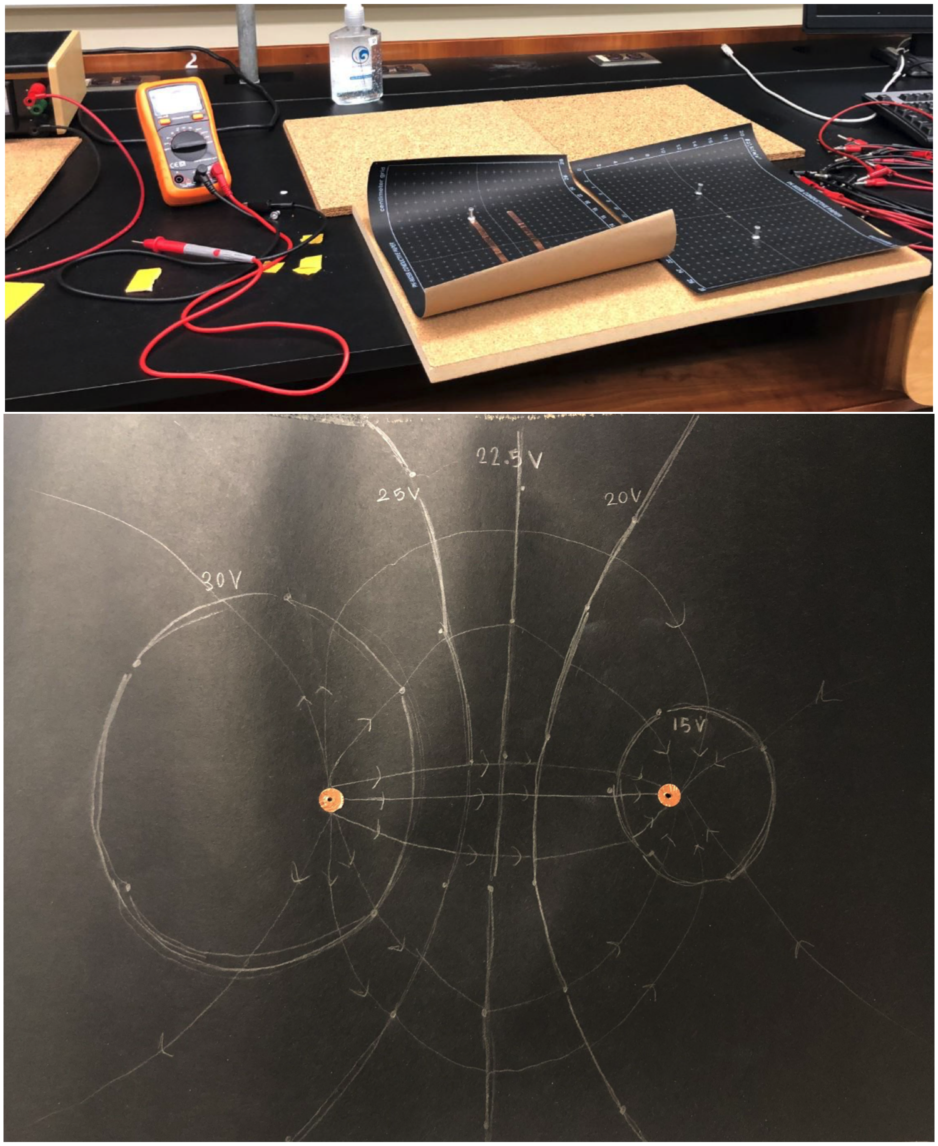


Figure 8.8: **E&M Electric Potential laboratory.** As preparation for applying the dipole model to the heart, in an earlier laboratory week, students first explore different types of electric potential configurations that can arise from different charge (current) configurations. One of the physical charge configurations they set up is that of an electric dipole, whereby they explicitly measure the equipotential lines, and then reason the electric field lines as the perpendicular lines through the equipotential lines.

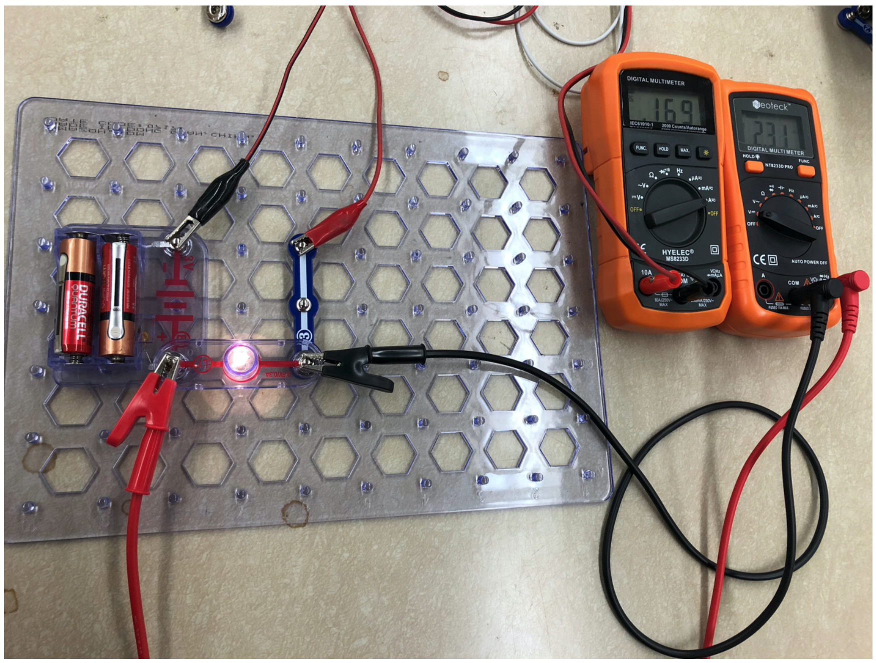


Figure 8.9: **E&M Electric Circuits laboratory.** In a laboratory week after the Electric Potential Lab and before the EKG lab, students gain practice setting up and measuring current and voltage across different elements in an electric circuit. Such hands-on experience with voltage and current, in conjunction with understanding of an electric dipole electric voltage field, paves the way for applying EKG leads to physical parts of the human body to take a potential difference measurement across the human heart.

8.4 Pre-Laboratory Assignments

In the revised UCLA IPLS, information about the background physics content and the physical setup/methods of the laboratory were shifted into a Pre-laboratory assignment that was due for completion credit one hour before the laboratory started. As can be seen in Figure 8.1, there is a lot of information that is relevant to student understanding of why they are doing the experiment, and specifically how, specifically, they use the materials in the experiment to accomplish their goal. In the revised laboratory manual, shown in Figure 8.2, much of this information is missing. Therefore, it is important to supply this information to the students, in such a way where they feel supported, and not overwhelmed.

Previously, the pre-assignment for the students would be to just read the manual before coming to lab, assuming that the student would be able to understand the topics through reading the material alone. While literature on this "flipped" classroom approach to learning does support student learning from pre-class reading before a lecture, evidence in this area also shows that students are not likely to put in the same effort into preparing for the class if there is no explicit reward for their efforts. On the one hand, students may not put in the effort to fully read the materials or visualize their experiment in advance because they do not feel external pressure to do so, thinking that they can make up the effort during the laboratory section itself. On the other hand, with such a large document and so many new ideas at the same time, students may also feel extreme anxiety and confusion over the vagueness around "understanding" all aspects of the experiment. Without prior experience in either the theoretical topics or the physical experience of doing the lab, how are students to know what is most important to prepare for, versus what is background information that can be referenced, as needed, at a later time? Evidence in literature also shows that there is a large difference in the synthesis abilities between experts and novices in disciplines such as physics. When physics experts design curriculum, there is often an underestimation around the extra energy and time needed for students to integrate and synthesize different aspects of the novel content. This creates situations where the designed problems or activities are much more difficult for students to solve than originally anticipated or designed.

With these considerations of student mental bandwidth, time, and emotional states, we created a unique pre-laboratory activity for each lab, such that students would be able to prepare for the laboratory, in both theory and practice, on their own time, with scaffolded

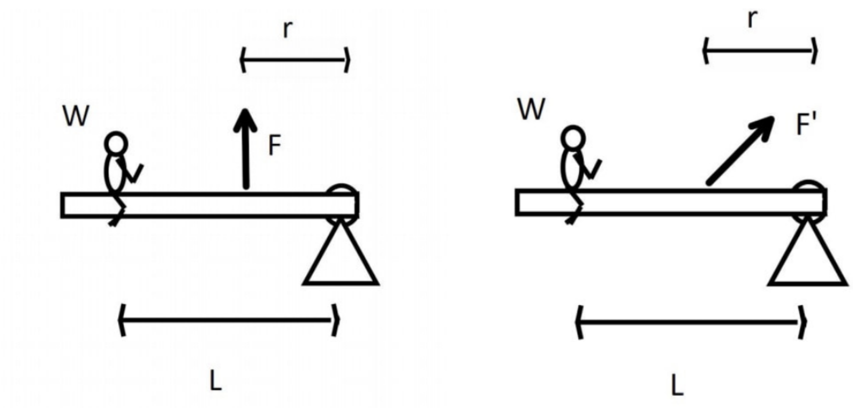


Figure 2: (left) Diagram for pre-lab slide 2. (right) diagram for pre-lab slide 3.

Pre-Lab Slide 3: Balancing forces in a Seesaw oriented like Human Bicep: Now, consider that the rope tension balancing the torque is at an angle, rather than being vertical (Figure 2, **right**).

a. State whether the magnitude of this new force F' needs to be larger, smaller, or the same size as the previous (vertical) force F in order to balance the seesaw.

b. Explain your reasoning using words and logic. (Hint: the force F' is a tension oriented along the direction of the rope).

c. Provide math (equations, geometry, trigonometry) as evidence for your reasoning. (Hint: Torque is **perpendicular** force x distance from pivot, and equilibrium mechanics requires balancing torques).

Figure 8.10: **Pre Laboratory Questions, theory practice.** This figure shows example 5AL pre laboratory questions about torque, given that the forces may point in different directions and occur at different locations from the fixed point of a fulcrum. Students are supported through three distinct types of problem-solving that guide them from lower to higher order problem-solving along Bloom's taxonomy levels. Such a type of problem is found in their textbook, and so students are able to connect the physics theory for this laboratory to what they are learning about in class.

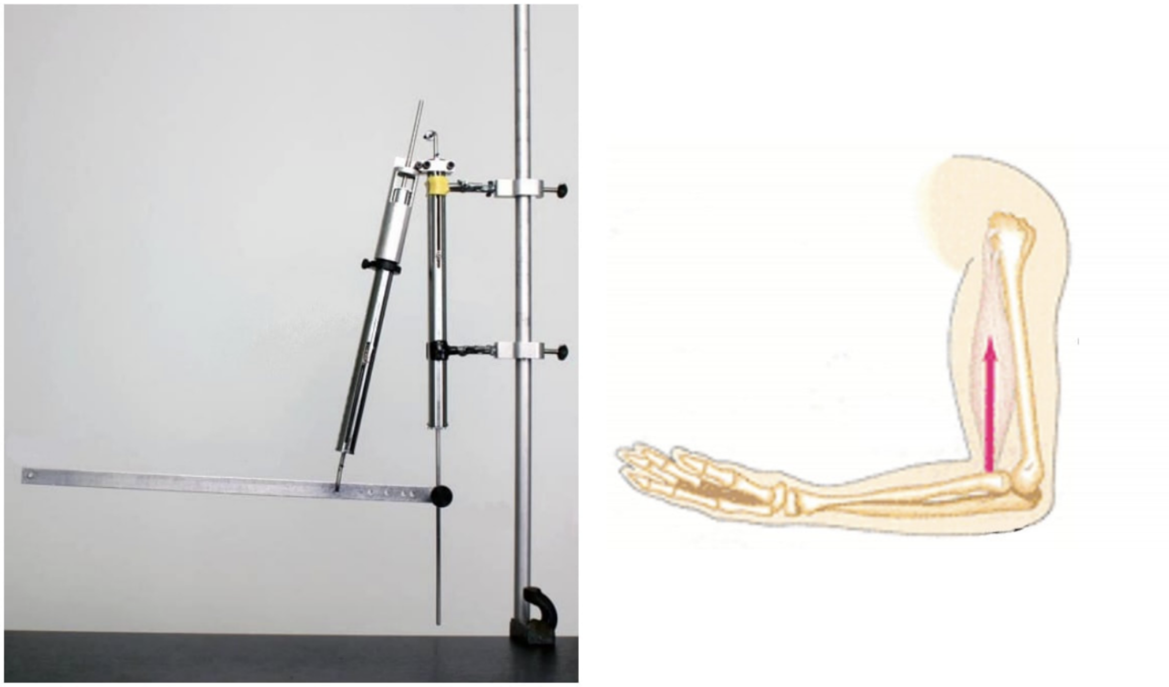


Figure 3: Setup for Lab Bicep Model, with biological arm schematic for comparison. Note: the biological arm has the bicep vertical, but in our model, we will have the bone vertical (as the pivot anchor), and the bicep muscle at an angle. Remember that the muscle is at an angle.

Figure 8.11: **Pre Laboratory Questions, methods diagram.** This figure shows example 5AL pre laboratory diagram that follows, after students have completed the theoretical questions about torque. **Left.** A photograph of their anticipated experimental setup, without labels. There are not labels, so that students can first formulate their own questions and create their own confusions, internally, before being given extra information. **Right.** A schematic of human system that serves as the motivation for the model. Nothin is labeled, so that students can decide for themselves what is the important aspects of the figure, and make the comparisons between the model and the system, for their own self, before coming into lab. **Bottom.** Within the caption for the pre-laboratory figure, the important information is provided, regarding the orientation of the important components in the model, compared to how they are shown in the schematic.

support regarding what is most important to think about before coming into the lab. Much information from the old laboratory manuals was reformatted into a new document, whereby students would be able to read about background information both specific to the lab, as well as theoretical information in their textbook, before working through a sequence of specific questions that guided their thinking to synthesize practice and theory in preparation for their lab work. An online google document template was supplied to them, as well, such that they could format one slide, as they chose, for their answer to each question, and be supported in the structure of their pre-laboratory submission. Emphasis was placed to focus on the important aspects of the question, to write concisely, and to build upon their own current understanding. Students were encouraged to explain their reasoning even when they were not confident about a question, through the assurance that their pre-laboratory work would be graded on effort and not correctness.

In some cases, the original laboratory manual had already been designed to have such scaffolded and relevant questions for students to consider, as part of their pathway for making sense of theory and practice in the laboratory. In other cases, when no such scaffolding had been created, or in the cases where the laboratories were designed from scratch, the textbook served as a great resource for designing pre-laboratory questions and content organization. We would like to acknowledge that some helpful revisions had already been created for a couple of the mechanics laboratory, and the changes that had been made to the lab manual did support our efforts for the construction of these pre-laboratory assignments. For example, the example pre-lab question shown in Figure 8.10 was adapted from a laboratory manual where prior efforts had already introduced critical thinking questions that students were encouraged to consider before physically setting up their experiment in the laboratory.

Logistically, pre-laboratory assignments were made available to students several days before their laboratory section, and were due one hour before their laboratory started. Each student was required to submit their own pre-laboratory assignment, but they were encouraged to consult one another and work together if they so chose. Pre-laboratory template pages were downloaded from the course website, along with the pre-laboratory assignment background. Students were responsible for saving their Google Slides sequence (scaffolded by the template), into a PDF with fixed number of pages, and then submitting their PDF onto their laboratory course GradeScope page, having logged in under their own GradeScope username. The laboratory website and GradeScope are discussed in future sections.

8.5 Online laboratory website

UCLA IPLS laboratories cannot supply information to students through the conventional methods an instructor syllabus and course CCLE (Moodle-based Collaborative Learning Environment, similar to Blackboard), because, in general, students within the same laboratory section do not necessarily share the same lecture course instructor. Due to general scheduling constrains and the magnitude of UCLA IPLS enrollment numbers, there is a first come, first serve basis for students to enroll, via registrar for their combination of lecture section, discussion section, and lecture section, for their particular introductory physics course. When students sign up for a particular lecture section, they are directed to a small set of discussion (recitation) sections connected to that particular lecture section. However, when their options for laboratory sections span the entire range of all available laboratory sections for that course, which are also open to all students who have signed up for other lectures sections of the same course. In Fall 2017, the first quarter of our revised introductory physics series for mechanics, 750 students enrolled, across 5 lecture sections, with 25 laboratory sections filled with a mix of students from all lecture sections.

Previously, laboratory manuals were linked to the UCLA physics and astronomy department homepage, where static PDFs had been uploaded in an interface where students could print or download the manuals, on their own time. In practice, both TAs and students would just use the laboratory computers to pull up the manual, in PDF form during the lab, and three students would have to share the single screen to consult the lab, while also using the computer screen to plot and analyze their data. A small fraction of the students would read the manual before coming into lab, print out the manual ahead of time, or pull the lab manual up on their phone to read along if they did not have immediate access to the computer. Moreover, the printers in the labs either did not work or were not available for students to print out the lab manual or their results work, during the laboratory session.

Given all these constrains and priors, we created an online weebly course website, that contained, in a centralized location, all the information that students needed to know about UCLA IPLS laboratories. The link to this website only needed to be on every IPLS course instructor's syllabus, and students would be able to, on their, have access to their laboratory course content, the list of policies, assignment due dates, lab manuals, pre-laboratories, templates for all assignments, as well as links to background material that could supplement their reading in the textbook, that was relevant to the physics they would explore in particular lab activities. The website also contained links to the pre and post quarter surveys, a feedback form for students to give input about their laboratory experience if they desired, as well as learning outcomes for the overall laboratory series, as well as the learning outcomes for each individual laboratory of that week. Lastly, students, via the website, now had access to logistical information like their TA and LA emails, which contact information was not traditionally available to them, until their TA chose to email them first. Such centralization and organization of logistics and information allowed the laboratory experience to be more transparent and accessible to students, and encouraged students to be a more active member in their laboratory education, instead of feeling helpless, and frustrated that their laboratory experiences depended more on external factors than their own efforts.

8.6 GradeScope online assignment submissions

Previously, in UCLA IPLS laboratories, students would receive credit for showing up to lab, working in groups, and displaying their physical setup with graphs on the computer screen, to receive laboratory credit. The old lab manuals also had "extra credit" activities, whereby students would earn a small fraction of additional points that would accumulate in an "extra credit mills" category throughout the quarter. These points were confusing to students, because in order to obtain full marks on their laboratory course grade, they needed to follow through with a certain number of these "mills" activities, to reach a certain threshold, after which they would not earn additional points. Needless to say students were keen to keep track of even the smallest fraction of point, while also not wanting to continue to perform unnecessary lab activities at the end of the quarter, after they had fulfilled their "mills" quote, which would not longer earn them any additional laboratory credit points. Since UCLA IPLS student population are predominately pre-medical students who work hard to keep a high GPA, students were constantly asking TAs to relay their laboratory grades and keep track of their "mills" credits throughout the quarter.

While TAs worked hard to keep track of student attendance and laboratory grades, it was frustrating and logistically challenging to handle the magnitude of emails inquiring about laboratory grades and points. Students inherently found the logistics around "mills" to be confusing and frustrating for them. They were especially vocal when the last name of the TA happened to be "Mills," in which case the students would inquire as to whether the TA had designed this obscure point system, and whether it could be modified. Upon such inquiry, TAs would reassure their students that this was an inherent aspect of the labs that was created far before their time. The naming convention was because each "mill" was technically worth one-thousandth of their final course grade, as they needed to accumulate 15 "mills" points throughout the quarter, the "mills" points category comprised ten percent of their total laboratory grade, and their laboratory grade comprised fifteen percent of their total course grade. At this point, the student's eyes had generally glazed over, and it was clear that such laboratory logistical practices were causing more harm than help to the students.

Therefore, to organize student participation credit, grades, and general feedback to students about their laboratory work, all credit and points organization between TAs and students was shifted to an online platform called GradeScope. GradeScope allowed every laboratory to have its own "course" page, whereby TAs could create and control assignment repositories and due dates that were unique to each laboratory sections.

In fact the UCLA IPLS laboratories were a pioneer in utilizing GradeScope for academic purposes at UCLA. Usage of GradeScope in the labs provided valuable experience and feedback back to GradeScope and UCLA academic divisions, regarding how to optimize the online grade and assessment feedback platform for students, in real-time throughout the quarter. Due to our pioneering efforts to use GradeScope in UCLA IPLS laboratories, now the entire UC system has a contractual relationship with GradeScope that standardizes and integrates GradeScope into UCLA's Moodle-based CCLE online learning platform.

As discussed in the previous assignment sections, GradeScope allowed for students to be in charged of submitting their own work, on their own time, for credit and grading. Additionally, GradeScope allowed for TAs to view and provide feedback to students in a more transparent way, that students could reflect on and apply to the next laboratory. Students were now able to check on their course laboratory grade through the quarter, and even inquire about aspects of the grades or credit through a GradeScope function called a "Regrade Request." If the TA had made a mistake or missed an aspect of their work, the student could flag the assignment, along with the rubric item associated with the grading, and voice their assertion about how their work is in alignment with the rubric and deserves the credit. In such a way, GradeScope allows for greater equity and transparency for student feedback and grading, especially in the case, such as UCLA IPLS laboratories, where TAs are entirely responsible for student assessment and a reasonable portion of the student's overall course grade.

8.7 Learning Assistants

UCLA IPLS laboratories have benefited tremendously from the support of the UCLA CEILS Learning Assistant (LA) Program. The learning assistant program trains and facilitates the logistical and pedagogical support to award upper division course credit for undergraduates who are experienced in particular UCLA course, such that they return to the class later in an educational role to facilitate student critical thinking and problem-solving among their peers. The introduction of LAs into UCLA IPLS laboratories has increased equity and accessibility of intellectual and emotional resources to our diverse population of UCLA's IPLS students.

In order to achieve our learning outcomes that students increase their enthusiasm and appreciation for physics application to their own life and the real world, it is important that students feel supported while they explore challenging physics topics and often make mistakes during their hands on laboratory experience. Undergraduate LAs, as part of their training through the LA program at UCLA, train in teaching and learning pedagogy, whereby they gain skills to ask particular types of questions that support students in their prior knowledge, while also encouraging students to explore new ideas and listen to one another in group conversation. Independent of the TA training, it is helpful to have supportive undergraduate peers in the laboratory sections, who not only understand the content and logistics of the laboratory (having experienced the coursework recently themselves), but also who have compassion, empathy, and insight into learning experimental physics from the perspective of being a life sciences student.

The LA program was first implemented in UCLA's Physics and Astronomy Department in Fall 2015, for two lecture sections of UCLA's IPLS mechanics course, and some of the associated discussion sections. Through this implementation, it was shown that not only did UCLA IPLS students enjoy and appreciate having the support of LAs in their lecture and discussion sections, but also that students with LAs in their discussion sections actually had increased mechanics conceptual learning gains, compared with students who did not have LAs in their discussion sections. While the LA program is an asset to students in their coursework, there are certain resources that the course instructor must provide for LAs in order for the UCLA LA program to be able to achieve its learning outcomes for LAs themselves. The course must be taught in an interactive and pedagogically student centered way in order to LAs to be able to engage with students in a supportive way. This means that the ability for LAs to be implemented in the Physics Department at UCLA depends not only on undergraduate student interest in serving as LAs for a prior course, but also it depends on the teaching style of the course instructor, and the instructor's ability and willingness to mentor LAs as well as teaching the course in a manner that supports LAs to support students.

Given the successes of LAs in physics lecture sections, we were motivated to implement LAs into the UCLA IPLS laboratory sections. Given that laboratory sections are by default peer-based, group interaction, where TAs only lecture for a maximum of ten minutes at the start of the class, LA support intrinsically supports laboratory section logistical structure and learning objectives. We were faced with a challenge, however, of how to provide the logistical and pedagogical support for the LAs themselves, such that LAs were able to review the coursework, and work with a course instructor to prepare themselves for the specific pedagogy and content skills necessary for their fieldwork experience in the laboratory sections.

Given that there was not a centralized instructor for the UCLA IPLS laboratory sections, we first piloted the LA program under the mentorship of a single graduate TA, who was technically hired as the Lead Laboratory TA (LLTA), for all of the UCLA IPLS Mechanics laboratories in Spring 2017. During spring the mechanics labs have lower than average student enrollment, so that there were only 12 sections of laboratories, compared with 25. The LLTA was able to host weekly content meetings for the LAs, while managing meetings and content for the TAs who were, together, hired to teach all the laboratory sections. Logistical structure that was already in place to support TA preparation for their laboratories was modified and implemented to support LAs for their unique combination of pedagogy and critical thinking so that they could optimally support to their undergraduate peers in-real time during the laboratory sections.

Overall, this pilot of the LA program in UCLA mechanics IPLS laboratories was a huge success, and this motivated us to broaden the scope of the LA program to all IPLS laboratories, starting Fall Quarter 2017, as we rolled out our revised IPLS curriculum. We maintained LAs in the mechanics laboratory in Fall Quarter 2017 (and onwards), introduced LAs to the revised thermo/fluids/oscillations laboratory in Winter Quarter 2018 (and maintained onwards), and introduced LAs to the revised Electricity, Magnetism, and Modern Physics laboratory in Spring Quarter 2018 (and maintained onwards).

Such rate of expansion required extensive cooperation between staff, faculty, and graduate students, such that there was a constructive and safe learning community space for all enrolled students, LAs, and TAs involved in the UCLA IPLS laboratory environment. Student outcomes and instructor responsibilities needed to be explicitly articulated and discussed, through the quarter. Content meetings needed to be aligned with both LA and TA expectations. Communication needed to be bi-directional between undergraduates and graduate students, such that there was consistent opportunity and avenue for constructive feedback, for all parties involved.

We know that we have succeeded in implementing the LA program, through the universal positive feedback from students, in their LA mid-quarter surveys and laboratory-specific surveys that we have implemented at the end of every quarter. Through concerted effort of select staff, faculty, and graduate students, LAs themselves have also felt supported in their personal skill development regarding both physics content and pedagogy training, as well as in the extreme benefit they have provided for their peers in their undergraduate physics education.

Additionally, there are select undergraduate LAs who have gone above and beyond in their contribution to the revised UCLA IPLS laboratories. They are mentioned in the acknowledgements section, and brief attention is given to particular accomplishments here. There were numerous instances where experienced undergraduate LAs, with graduate students, faculty and staff, provided feedback for the development of laboratory course materials, facilitated UCLA extension laboratory sections, mentored new undergraduate LAs, facilitated TA pedagogy training, optimized laboratory procedures, debugged laboratory equipment, and even collaborated in analysis of UCLA IPLS laboratory revisions assessment results to assess the efficacy the the laboratory revisions.

8.8 Teaching Assistants

For as long as UCLA IPLS laboratories have been in practice, TAs have been essential for supervising and mentoring undergraduate students. Much of the logistical and pedagogical planning of the revised IPLS laboratories depended on the resources, logistics, abilities, and expectations of the TAs who would be intimately affected by any laboratory revisions.

On the one hand, we benefited from pre-existing structure whereby TAs were already used to reviewing teaching materials and guiding students through their laboratory practice. We also benefited from the fact that most TAs with UCLA IPLS laboratory experience were in agreement that the laboratories were not conducive to learning and that laboratory revisions made sense to support increased student learning. On the other hand, TAs were not particularly enthusiastic about needing to provide additional student formative feedback, in the form of grading pre-laboratory and during-laboratory activities. They also expressed some hesitancy in facilitating more open-ended laboratories where it was not always clear what the "right" answer was, and it was often necessary to facilitate dialogue and critical thinking among the students to make sense of the laboratory setup or experimental results.

Such difficulties are not explicitly the fault of any graduate student, but rather the challenging situation that graduate students are placed in, to balance their teaching employment with their graduate level coursework and their PhD research projects. While graduate students are often employed via teaching contract to work a fixed number of hours per week, they are often encouraged by their thesis advisors (and department) to prioritize their coursework and research, such that they can graduate as quickly as possible. Since most physics graduate students enroll in PhD programs to develop research projects, not to teach, it makes sense that their focus is on research, and the associated coursework required to complete their degree and gain their necessary experience to excel in their PhD research.

At the same time, such conflict of time and energy puts strain on the quality of education that UCLA undergraduates receive in their recitation and laboratory sections. Through fault of the R1 university system, TAs are often highly motivated to put in the absolute minimal effort required to fulfill their teaching responsibilities to the bare minimum of what needs to be done, such that they can keep their university employment positions, have their tuition paid for by the university, and collect their paycheck at the end of each month.

The addition of learning assistants to the laboratories was of great emotional and psychological support to TAs, and implementation of such support was leveraged in communication with TAs such that a middle ground compromise was met. Most TAs were willing to spend a couple additional hours per week to grade student work, when it was made clear to them that there were particular changes to the labs that would benefit them, in return, and the overall learning outcomes of the course were made explicit to them so they could see why we were asking them to put in this effort.

There were a small fraction of older TAs who were used previously putting in minimal efforts as a TA. In such cases, we were forced to just be explicit: that their slight change in responsibilities was part of a universal department-wide undergraduate student-centered curriculum optimization. Because our laboratory revisions were a universal and department-wide supported effort, in the end, TAs just had to accept the facts that they now had a little more work to do, in UCLA IPLS Laboratory TA assignments.

It should be noted that the entire fact that UCLA's physics and astronomy department can even support its large number of physics PhD students in the department, is due to the fact that UCLA IPLS physics courses draw in many undergraduate students, and therefore university funding external to the department, for TAs positions to all the lecture discussion and laboratory sections can be taught. If the UCLA IPLS laboratory sections had continue to be managed in such an unhelpful and arguably detrimental fashion for IPLS students, UCLA Life Sciences may have changed their curriculum policies within the Registrar, to teach their own physics courses and provide an alternate mechanism for students to achieve their physics credit for medical school. In such case that students could take take life-scieces focused physics courses within their own life-sciences division would mean that the UCLA physics department would no longer receive this funding for its graduate students to teach, and therefore be as easily financially supported by the University. Such internal shifts in registrar's course listing structure would have profoundly detrimental effects on the structure of UCLA's physics department. It would no longer be able to advertise itself as being able to support as many graduate students as it does, and its research standings would ultimately suffer, especially for its theoretical division, which generally require students to maintain teaching assistant positions for the majority of their time in graduate school.

Given all these factors, we were highly motivated to strike a common ground with TAs, create new structure for TA responsibilities documentation upon their hiring at the start of each quarter, and create avenues of communication for TAs to continuously provide feedback about their experience as a TA so that continual compromise could be created to find working solutions to challenges that would arise between student needs and TA needs during this complex Graduate Student Teaching paradigm.

In most cases, the UCLA IPLS laboratory TA assignments were able to be awarded to first and second-year physics and astronomy graduate students, who, in general, had less institutional memory of UCLA TA positions, and therefore less expectation regarding the nature of their exact TA responsibilities. The Physics and Astronomy TA training class was improved to focus specific training sessions on TA responsibilities during laboratories, along with support for TAs of examples on how to most easily facilitate student-learning in such environments without taking exorbitant amounts of time or energy away from the graduate student.

In all cases, TAs relied heavily on the pedagogical support and engagement of LAs who accompanied them in the laboratory classroom. In some cases, additional intervention was required to ensure that the TA continued to engage with all laboratory groups in the classroom, over the course of the section. When LAs were especially competent in their role, and that TA did not naturally have intrinsic interest in student engagement, the TA would sometimes just sit in a corner and watch the room without circulating the room or engaging with the students. In such cases it was helpful to have higher level department support to intervene and personally address the matter, individually with particular graduate students, when necessary. For the most part, this was not due to overt or malicious negligence on the part of the TA, but rather the fact that TAs, as humans in a stressful academic program, are often overwhelmed, and may carry intrinsic tendency for introvert nature and lack of interpersonal and communication skills. At the same time, TA management was a large part of these curricular improvements, and overall increased support for both students and the LAs who supported them, would not have been possible without the hard work of many

LLTAs, staff, and faculty, who worked together to maintain UCLA Physics and Astronomy department structure for graduate TA assignments and roles/responsibilities.

8.9 E-CLASS Pre/Post Quarter Assessment Analysis

We assessed our laboratory revisions through analysis of particular E-CLASS pre and post quarter survey results. Student post quarter responses were paired with pre quarter responses and answer choices were converted to numerical value, by converting "Strongly Disagree" to level 1, "Slightly Disagree" to level 2, "Neutral" to level 3, "Slightly Agree" to level 4, and "Strongly Agree" to level 5. With such conversion, we quantified pre quarter, post quarter, and during quarter attitude shift distributions for student attitudes. For this analysis, we focused specifically on the attitude shifts of students during the first quarter of our physics series, in their introductory mechanics laboratory. We chose these students because this was their very first exposure to physics at UCLA, and, for over one third of the students, it was their very first physics class ever. Our population of students in this analysis consisted primarily of second and third year undergraduates, fulfilling neuroscience, chemistry, environmental science, or pre-health/medical graduation requirements.

In the E-CLASS survey we specifically analyzed three particular assessment statements, one as our measurement tool, and the other two as controls, to asses how our laboratory was affecting students, in three different aspect of our critical thinking learning outcomes. Firstly, we considered how students identified with the E-CLASS statement, *When doing an experiment, I usually think up my own questions to investigate*, which we refer to, in shorthand, as "Asking Own Questions." Student feedback regarding "Asking Own Questions" was used as a measurement tool to probe how our laboratory revisions were shifting student perspectives towards feeling comfortable and confidence in asking their own meaningful questions during their own scientific inquiry process. In the pre-revised laboratory, student feedback had communicated that the laboratory manuals were too rigid and boring, and students had felt that they were merely performing actions during laboratory without finding meaning what they were doing. Since our mechanics labs had been designed for students to create their own scientific question during their pre-laboratory work and discuss their pre-laboratory ideas with their peers during their laboratory section, we hypothesized that our revisions would support students to show increased agreement with the "Asking Own Questions" statement.

Secondly, the two other E-CLASS statements that we tracked were chosen initially as controls, to make sure that we were adequately supporting students, while we were taking away much of their laboratory structure. The previous laboratories had a complete cook-book lab that students could follow to get their laboratory credit. Our revised labs front-loaded the important information into the pre-laboratory assignments, and left the students with much less material in their laboratory manual instruction sheet. Such lack of structure required students to autonomously review their pre-laboratory work with their group-mates and agree upon a procedure, as a group, to explore their specific experiment question. This meant that there could be considerable variation in laboratory measurements, across different lab groups, and students would not be able to look up the "correct answer" to many of their questions, upon encountering doubts or challenges. As such, we also assessed responses to the E-CLASS statement *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor*, shorthand referred to as "Ask Instructor." Additionally, we analyzed responses to the E-CLASS statement *When doing an experiment, I just follow the instructions without thinking about their purpose*, shorthand referred to "Follow Instructions." After a successful revision to create while more inquiry-based labs while supporting students with adequate resources, we hypothesized that students would show at least level, if not reductions in the degree to which they identified with these attitude statements.

To assess attitude shifts in our students, we subtracted the pre-quarter response value from the post-quarter response value, for each student, and calculated both the mean and median shift value. Likewise, we computed statistics on the mean and median value of both the pre quarter distribution, and the post quarter distribution, only including those students who had both pre and post quarter responses. To assess the statistical significance of these shifts, a Sign Test was used. In such a statistical test, the observed relative number of positive shifts versus negative shifts, was compared to outcomes from many independent simulations of randomly flipping two coins, labeled 1 and 2, the same number of times as there were subjects in the dataset under consideration. When the number of occurrences of increase from 1 to 2 is compared to the number of occurrences of decrease from 2 to 1 in the case of the dice simulation, one is able to estimate the statistical likelihood of observing our data results due to chance, given that there really is no difference in the pre quarter and post quarter population. Such a test required no assumptions about equating the magnitudes between adjacent level shifts, in the case, for example, of a shift from "Strongly Disagree" to "Slightly Disagree," or "Neutral" to "Slightly Agree." It also did not require any assumptions about a particular shape for the distribution of the data.

In all, we analyzed these assessment results in every quarter of our introductory mechanics for life sciences laboratory (5AL), for two years after our revisions: Fall 2017, Winter 2018, Spring 2018, Fall 2018, Winter 2019, and Spring 2019. We also analyzed the Winter 2018 5BL survey results, to assess how students may have retained their attitude shifts, after their first quarter of physics, or experienced additional changes during their second quarter of UCLA physics. Lastly, as a means to compare post revisions attitudes with pre-revision attitudes, we analyzed Fall 2017 assessment results from 6BL, which was the las quarter of the pre-revised laboratories, showing student feedback after they had taken the pre-revised introductory mechanics laboratory. While we did not have explicit pre-revised E-CLASS data for our mechanics laboratory, we were able to gain some pre-revisions vs. post revisions insights from looking at the 6BL assessment results.

8.10 Logistical Details

This work is supported by the UCLA Department of Physics and Astronomy, UCLA Division of Physical Sciences, UCLA Division of Life Sciences, and UCLA Center for Advancement of Teaching (CAT), formerly known as the UCLA Office of Instructional Development (OID), under two UCLA IIP Grants: *Physics Optimized for Life Science Majors: New Course Development of Physics 5 ABC and Labs*, AY17-18, and *Data-driven, Systematic, and Sus-*

tainable Transformation of Physics for Life Scientists, AY18-19. All experimental study design, assessment, and analysis was in accordance with the University of California, Los Angeles Institutional Review Board (IRB #19-000751, *Visual Acuity and Microsaccades* and IRB #19-000578, *Assessing Physics for Life Sciences*). Assessment data was analyzed using Rstudio. Scripts are available upon request.

CHAPTER 9

Results

9.1 Students Ask their Own Questions

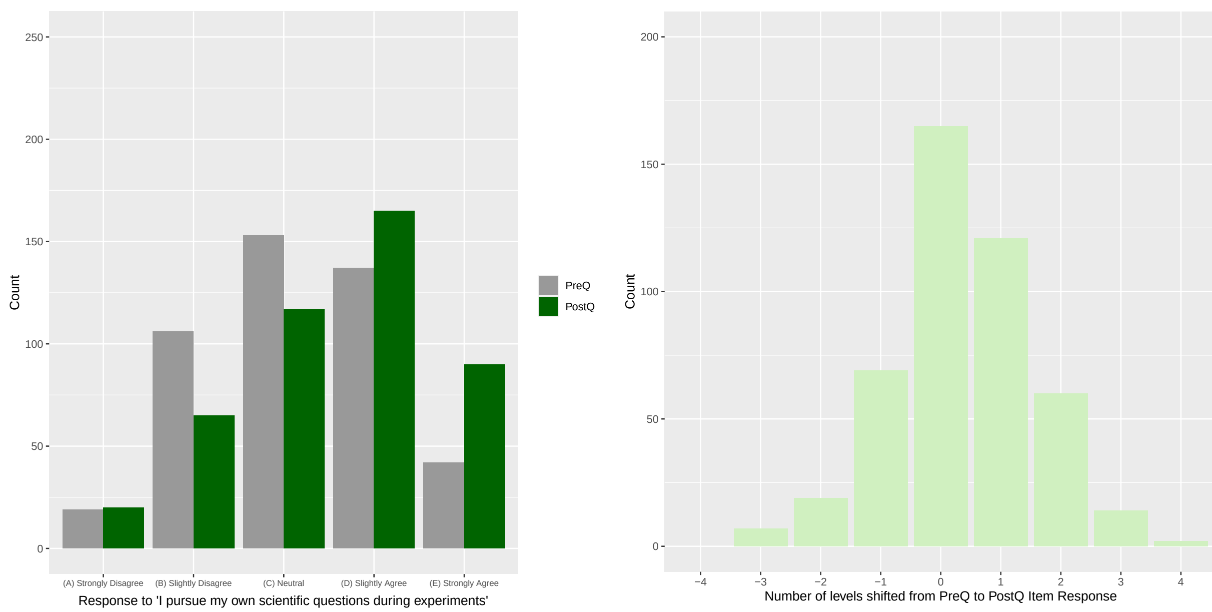


Figure 9.1: **Asking Own Questions** Likert Item Pre/PostQ responses, **5AL 17F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate*. **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.36 Likert Levels was shown to be statistically significant. N = 457. Additional statistics shown in Table B.18.

Figure 9.1 shows results from the very first quarter of laboratory revisions. Pre quarter mean was 3.17 while post quarter mean was 3.53. Average attitude shifts, for pre/post quarter paired data was 0.36, ($P = 2.4 \times 10^{-9}$). Students entered the class with a normally distributed range of attitudes around asking their own scientific questions during physics experiments, and they completed the class with an overwhelming shift in attitude towards more strongly identifying with asking their own questions. Such positive shift in attitudes towards asking own scientific questions was found for every subsequent quarter of the introductory mechanics laboratory. These data are shown in the appendix. Specifically, student attitudes about asking their own scientific questions continue to improved through future quarter offerings of our introductory mechanics laboratory. Specifically, in Fall 2018, exactly three quarters and one year later after we introduced the revised laboratories, we found that Pre-Post quarter attitude shifts had increased to 0.50 ($P = 2.4 \times 10^{-9}$). Pre quarter mean was 3.03 and post quarter mean was 3.52. Additional statistics are shown in the Appendix. Figure 9.2 shows these data.

As a follow-up to assess student attitudes in our revised introductory mechanics laboratory, we analyzed student attitudes about asking own questions for the subsequent lab in the series, 5BL, for Winter 2018. This meant analyzing data that contained primarily the same students shown in Figure 9.1, except tracking them through one quarter later, in their UCLA physics education. Figure 9.3 shows results from this first quarter of our revised 2nd quarter physics laboratory. Most notably, the pre quarter assessment results for Winter 2018 look extremely similar to the post quarter results for Fall 2017. While this may seem obvious, given that these two populations heavily overlap in having the same students, this is not necessarily a given, for curricular revision assessments. There is evidence to show that students often show temporary learning gains, perform as predicted in attitude assessments at the end of a quarter, only to return to the start of the quarter showing regression back to a more pessimistic outlook on the quarter. However, in our results, we show that we not only transform our student attitudes through their very first quarter of physics, but also, that we maintain these attitudes, so that they are near saturation, already, at the start of the next quarter. Additionally, in the second quarter of their physics laboratories, students again continue to show gains in their agreement towards identifying with the idea that they pursue their own scientific questions during experiments. Even with pre quarter results near saturation, average attitude shifts, for pre/post quarter paired data was 0.12, ($P = .046$).

Such results are indeed encouraging, but, as a final comparison, we directly compared these E-CLASS results from our post-revisions laboratory assessment data, to E-CLASS results from students who experience our pre-revised IPLS laboratories. Because we did not have E-CLASS data results for students in their pre and post quarter experiences of the pre-revised 6AL (mechanics laboratory), we instead looked at E-CLASS data results for students in their pre and post quarter experience of the pre-revised 6BL (2nd laboratory in the series) data. We were particularly interested in the pre quarter data for these assessment results, as a proxy for post-quarter results for those same students in their pre-revised me-

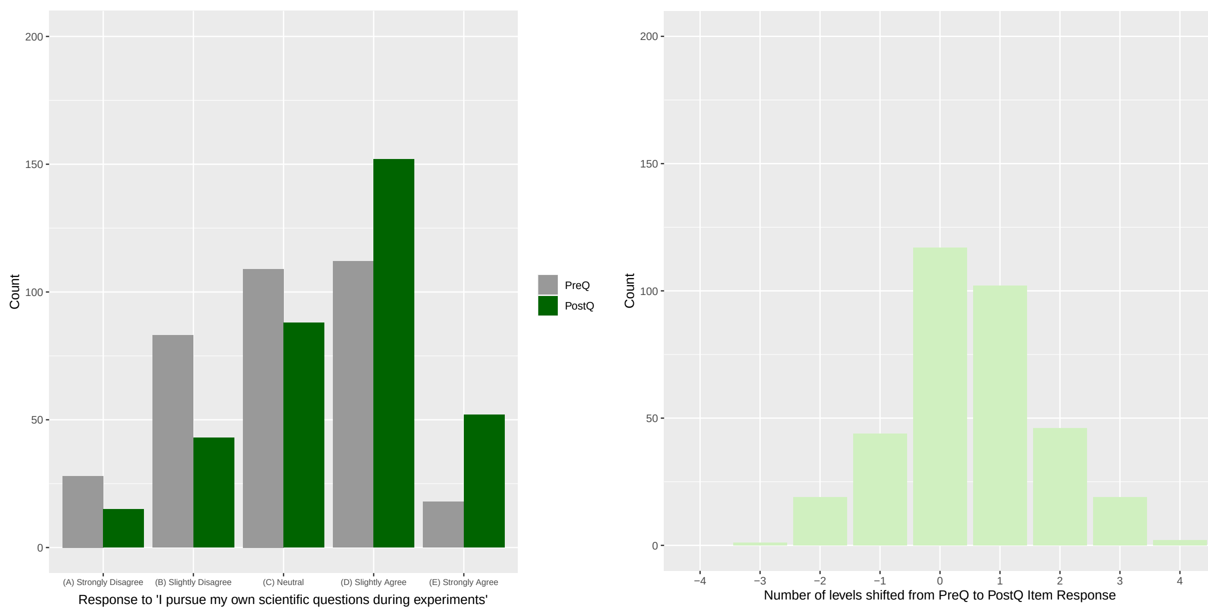


Figure 9.2: **Asking Own Questions** Likert Item Pre/PostQ responses, **5AL 18F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.50 Likert Levels was shown to be statistically significant. N = 350. Additional statistics shown in Table B.21.

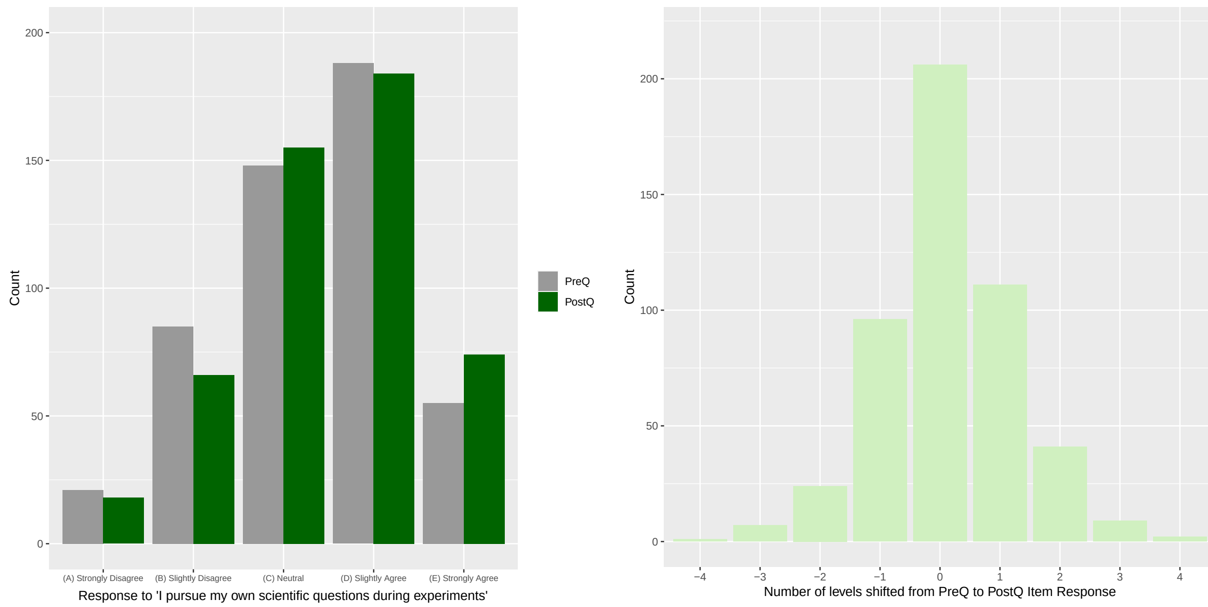


Figure 9.3: **Asking Own Questions** Likert Item Pre/PostQ responses, **5BL 18F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.12 Likert Levels was shown to be statistically significant. N = 497. Additional statistics shown in Table B.24.

chanics laboratory experience. Indeed, there is stark contrast between the pre-quarter data in Figure 9.3 and Figure 9.4, which shows results for the pre-revised laboratory pre/post quarter E-CLASS survey. Specifically, the students in the pre revised labs show overwhelming pre quarter disagreement with the idea that they pursue their own scientific questions in experiments. Given the assumption that there is typically a normally distributed pre-quarter population upon beginning the physics series (which is reasonable given that all of our post-revised laboratory data show a normal pre-quarter distribution for this question across all the first quarter mechanics laboratory data), then 9.4, shows that students actually shift toward an increasingly negative alignment with this statement about making their own questions. As such, there is evidence to suggest that our old IPLS laboratories were actively discouraging students against thinking up their own questions, in favor of just doing what they though was the correct actions to take to quickly finish the lab and get a good grade in the class. On a positive note, it does look like the pre-revised labs were supporting students to ask more questions later in the next course in the laboratory sequence, but, even then, it was only bringing students back to attitudes that resembled the normal distribution that they had originally had when starting the series in the first place. The distribution of post quarter results in 9.4 is considerably different than the distribution of post quarter results in 9.3.

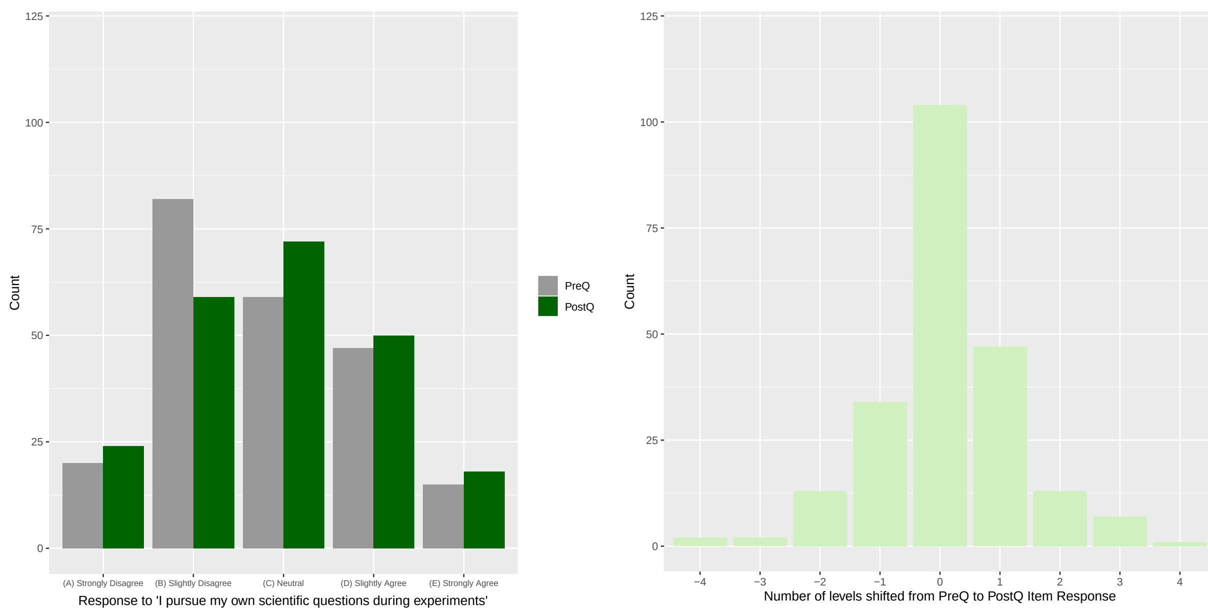


Figure 9.4: **Asking Own Questions** Likert Item Pre/PostQ responses, **6BL 17F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.11 Likert Levels was not statistically significant. N = 223. Additional statistics shown in Table B.25.

9.2 Students Ask the Instructor for Help

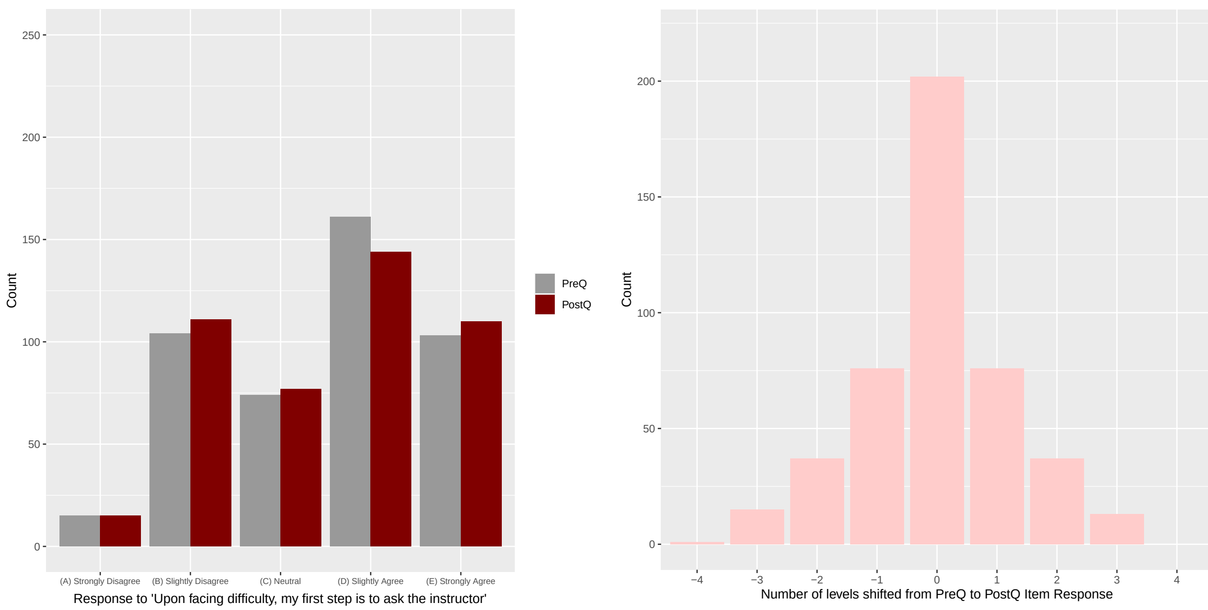


Figure 9.5: **Ask Instructor** Likert Item Pre/PostQ responses, **5AL 17F**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.02 Likert Levels was not statistically significant. N = 457. Additional statistics shown in Table B.18.

While we hypothesized that we would see gains in regards to students asking their own scientific questions, we were not sure whether students would still be supported to work through problems with their own resources, critical thinking skills, and persistence problem solving strategies, or whether they would be more inclined to rely on the instructor for support. On a positive note, we did not see that students had attitudes shifted increasingly more towards relying on the instructor for help. However, we also did not see any gain toward our learning outcomes of increasing student critical thinking and persistence learning attitudes.

Moreover, because the student's pre quarter attitudes were already skewed towards positively identifying with the statement, we considered our laboratory revisions to be failing in achievement of this particular learning outcome. Specifically, results from the pre revised laboratories provided evidence that in past laboratory settings students were not relying entirely on their TA laboratory instructors, to complete their labs. This meant that it was possible for students to re-build confidence in their resources, and exercise their own critical thinking as a first step when they had a problem. Average attitude shifts, for pre/post quarter paired data was -0.28, ($P = 6.2 \times 10^{-4}$). As such, we focused efforts to make the lab manuals more clear, remind students to review their pre-laboratory work for the first 15 minutes of every laboratory section, and we worked with TAs and LAs to focus efforts on reminding students

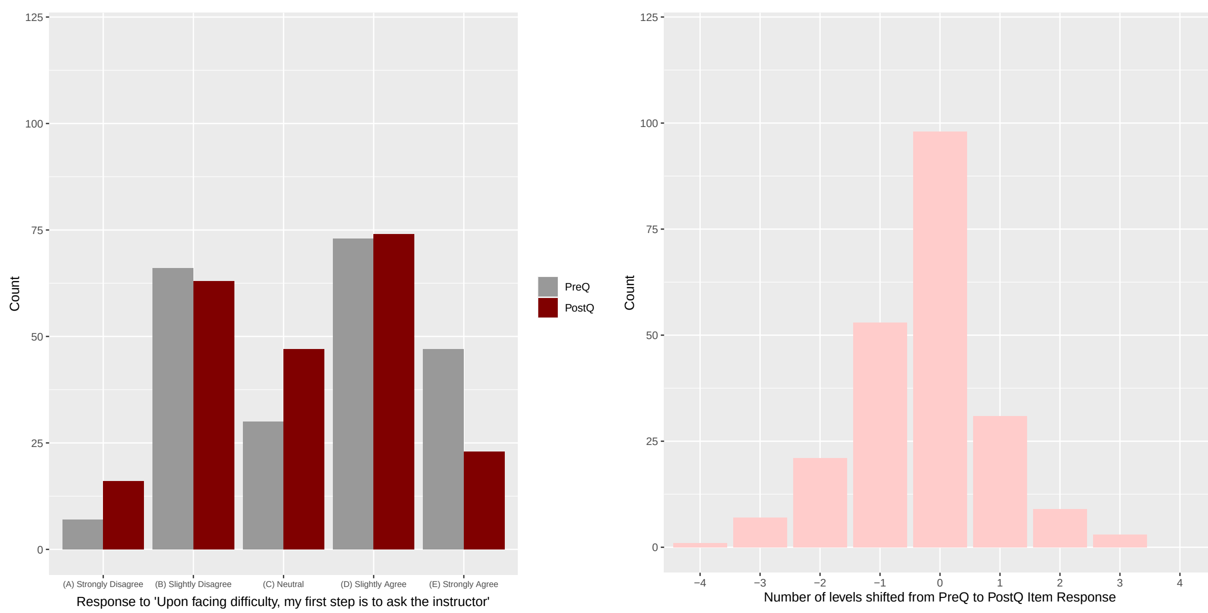


Figure 9.6: **Ask Instructor** Likert Item Pre/PostQ responses, **6BL 17F**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.28 Likert Levels was statistically significant. N = 223. Additional statistics shown in Table B.25.

about the resources that were already available to them, instead of immediately answering their every question. Additionally, a particular intervention was introduced, that forced students to display their "working status," by means of a Red/Yellow/Green card system that provided visual information as to whether students were happily working or whether they were stuck on a problem. Details about the Red/Green/Yellow card system are discussed further in the Appendix.

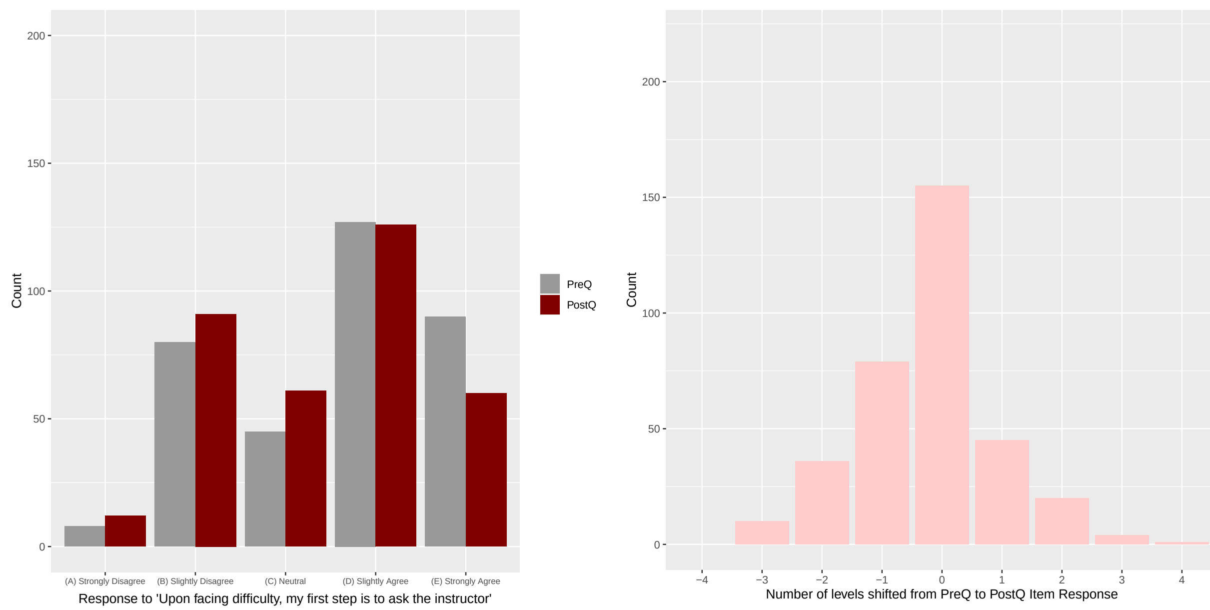


Figure 9.7: **Ask Instructor** Likert Item Pre/PostQ responses, **5AL 18F**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.23 Likert Levels was statistically significant. N = 457. Additional statistics shown in Table B.21.

Figure 9.7 shows the attitude results, the quarter following this second round of laboratory revisions. Average attitude shifts, for pre/post quarter paired data was -0.23, ($P = 1.0 \times 10^{-4}$). From our second round of revision efforts, we were able to recover our desired shift towards students building their own critical thinking and problem solving autonomy skills.

9.3 Following the Lab Manual Instructions

We used the third E-CLASS statement, *When doing an experiment, I just follow the instructions without thinking about their purpose*, as a control to make sure that we were not modifying the curriculum such that student behavior was changing drastically, in relation to how they were using the laboratory manual. Given that student pre quarter attitudes are very shifted towards expecting to NOT blindly follow the laboratory manual, our goal was just to show that students were not shifting towards thinking that they needed to use their lab manual instructions over their own critical thinking. Overall, our results confirmed this goal. Additional statistics are shown in the Appendix Section.

CHAPTER 10

Discussion

10.1 Overall improvements to IPLS structure and pedagogy

Design, development, and implementation of learning outcomes, pre/post quarter assessments, activities, pre-laboratory assignments, website, GradeScope, LAs, and integrated communication of all stake-holders, UCLA's IPLS laboratories have been improved. This structure is documented and accessible to the department, so that future IPLS laboratory experience can be organized and pedagogy-based, with a focus on student-centered, inquiry-based learning.

10.2 Students Ask their Own Questions

From particular attitude assessment data, it is evidence that these laboratory revisions have created inquiry-based environment where students spend increased time asking and pursuing their own scientific questions. From the beginning, the introductory mechanics laboratory was designed to be inquiry-based. It has been shown to be a success in this category of its design. The curriculum was emphasized to support students to deign their own options for experimental questions during their pre-laboratory assignment, and to come together as a group at the start of their laboratory and converge upon a plan for their experimental inquiry together. The student attitude gains show that such intervention and curriculum design does indeed shift student attitudes towards increased perception of asking scientific questions, and it does so more than the previous curriculum at UCLA was able to do.

We found evidence that, before the laboratory revisions, students had minimal attitude shifts regarding their perceptions about developing their own questions during an experimental experience. They started the quarter with attitudes that, on average, resembled a normal distribution, centered at "Neutral," regarding their ranking of their level of own questioning, and they ended the quarter, with very similar distribution. A pair-wise attitude shift analysis also shows that "Own Questions," had minimal shifts. While these data are for the IPLS course offered after the mechanics course, and we do not have direct attitude results for this question from the pre-revised mechanics IPLS students, it is logical to conclude that the pre-quarter results for this quarter's worth of data must be strongly correlated with the post quarter results from our pre-revised labs mechanics student data, as they are of highly overlapping subject pool.

In stark comparison, the post-revisions mechanics IPLS laboratory results show marked shift in student attitudes around this "Own Questions" statement in the preQ/postQ survey results. Moreover, the preQ data through every quarter is very consistent, except for the preQ data for the next sequence of IPLS laboratory in the post-revised labs AFTER our intervention. This means that not only do students show a huge shift in asking their own scientific questions through our laboratory intervention, but that they maintain this way of thinking, going into their future rounds of laboratory sections, and upon leaving these later rounds of physics laboratory sections.

10.3 Students autonomously problem-solve

On another interesting note, when Fall 2017 6BL (pre-revised) preQ student data is about "Own Questions" is compared with all of the 5AL mechanics (post-revised) preQ student data, it can be seen that the preQ distribution is actually shifted more negatively. This suggests that the pre-revised mechanics (6AL) laboratory classes were not only failing to improve student attitudes in the domain of asking their own questions, but that they were actively worsening the student attitudes.

Through every single quarter of 5AL, from Fall 2017 to Spring 2019, the pre/postQ data around asking questions has shown that UCLA IPLS students now have increased attitudes about asking and pursuing their own scientific questions during experimental inquiry.

Even though the first round of our revisions did successfully improve student questioning during laboratory, the nature of the revisions also caused students to need more help from the instructor during their laboratory section. One of our outcomes for students was to develop their critical thinking skills and ability to problem solve through challenges without relying on the answer from their instructor, so quickly. Therefore, we implemented and analyzed another attitude question, this time asking student agreement around the following statement, *When I encounter a difficulty during an experiment, the first thing I do is ask an instructor for help.*

We found that students show increased shift towards agreeing with this statement, even though, in the pre-revised laboratories, evidence points to the fact that they ddi not identify strongly with this statement. Therefore, in a smaller, more pedagogically-focused second round of laboratory revisions in Fall 2018, we focused efforts on emphasizing student autonomous thinking, group engagement, and consultation of personal resources, in a Red, Green, Yellow Card display system.

While the specific nature of this Red, Green, Yellow Card system is discussed more in the Appendix of this thesis, the take-away message of our results shows that serious analysis of assessment data, and evidence-based future rounds of revisions, can produce dramatic improvements to student learning and attitudes, in short amount of time. By working together as a learning community, and from a data-driven, evidence-based perspective, we were able to achieve similar attitude shifts of students increasing their perception of their learning persistence that were present from before the laboratory revisions. However, instead of the students not needing the instructor help because the laboratory manual was a recipe-based set of instructions, we believe that students are now recognizing their autonomy *emph* abilities, by working more effectively in groups and utilizing their diverse set of resources (pre-lab, textbook, inquiry-based laboratory manual, and even researching information online).

CHAPTER 11

Conclusions and Future Direction

11.1 Moving to Online Remote Laboratory Instruction

In conclusion, our physics laboratory revision efforts show concrete attitudinal shifts in UCLA life science majors. Assessment results show evidence that students are more frequently asking and pursuing their own scientific questions in their physics laboratories, while exercising their own critical thinking regarding their own resources during challenging problem solving. Such revision efforts have been successfully carried forward for three years, until unfortunate disruption due to the Corona Virus Pandemic.

Interestingly enough, many aspects of these laboratories have proven robust to the challenging times of mandatory remote online instruction. The "flipped" nature of the pre-labs, whereby students autonomously practice with the material before engaging with an instructor, are entirely accessible in this remote instruction environment. Additionally, many aspects of having the students create their own scientific predictions, and outline how they would go about doing their experiment, before doing it, are entirely accessible in online format, even when students do not have physical access to the laboratory equipment. Lastly, some aspects of laboratory equipment, like the Snap Circuit hardware in the 5CL electricity and magnetism laboratories, are able to be purchased and delivered to students, in their homes across the world, such that they can practice, hands on, with the material, from their remote, online environment.

Additionally, the collaborative learning community that we created involving faculty, staff, graduate teaching assistants, and undergraduate learning assistants, is still as strong as ever, and such network of support has proven invaluable to students during this stressful time of fear and uncertainty. Our labs have adopted a zoom-classroom, whereby each TA has their own zoom room for students to enter during their laboratory session, and to break out into their laboratory groups via zoom breakout rooms. Undergraduate learning assistants and the TA are able to move between the breakout rooms, and support students as they work collaboratively on their laboratory problem solving, in combination of theory and practice. While some students in each group physically have the equipment, others in the group support by researching theory to build predictions about results, asking questions to double-check the correct experimental setup, or reviewing textbook or class notes to figure out how to make sense of results. Because our labs are now student-centered and inquiry-based, there are so many more opportunities for students to remain engaged with the laboratory curriculum, even when they do not have physical access to the laboratory equipment themselves.

Lastly, our previous intervention with the Red/Yellow/Green Card system, has proven useful, in adaptation, to organize student progress during online laboratory sessions. Instead of students displaying their collective laboratory group status physically via a colored card at their lab-station, now each student, individually, has access to an online google spreadsheet that has a row for their name and a series of columns that sequentially outlines particular check-points throughout the lab. Each student is responsible for moving through each cell, in their row, to show their progress, and status, throughout the laboratory class. Specifically, students turn their status to green when they are complete with a checkpoint, they turn the cell to yellow, when they are working on it, and they turn the cell to red, when they have a problem and they are stuck. It is of interest to us to modify this tactic, slightly, such that students differentiate between "working" on a task, and "stuck" on a task, such that they can set a time for the TA to know to let them struggle for some time before immediately answering their question. In practice however, if TAs and LAs can keep track of the order in which students have questions, there is usually sufficient delay time before the instructor can support the students, such that the students have some nonzero amount of struggle time before being attended to. Overall, it is rewarding to see that some of our past pedagogical implementations have proven useful during our transition to online laboratory instruction.

At the same time, during this time of unique learning experience, it is also especially important to be taking assessment data on students, in such a way such that their feedback can quickly be processed and implemented into real time curriculum adjustments. It is important to keep curriculum student-centered and flexible during this time, and our revised laboratories allow us to more easily adapt to the needs of our students.

11.2 Further Assessment Analysis

11.2.1 RGY Cards

We still have unanswered questions about what exactly shifted student attitudes, in the second round of revisions, such that they were less inclined to immediately ask the instructor for help upon facing a challenge during experiments. As mentioned in the Appendix, we have observational data of students using the Red Green Yellow Card System (or not), and we find surprising results that physically forcing the students to use the cards may backfire, while, remind the students to critically think may be the solution. In our observations where we saw that the students did not use the cards, the TAs and LAs may have still been focusing on fostering critical thinking by remind the students to consult their own resources, or asking the students specifically about the resources that should be consulting before immediately asking for help.

Given these open questions, it may be worthwhile to continue to observe laboratory sections, if there is interesting in implementing the Red Green Yellow Card system again. It is interesting to note that student attitude grains in this area started to shift BACK towards neutral, by Spring Quarter 2019. During this time the Red Green Yellow Card System was not being actively administered, so it is possible that this system was helpful for students, at least in the start of the quarter, to get them to focus on critically thinking amongst themselves instead of immediately raising their hand to ask for instructor confirmation. If the opportunity arises, we would be interested to implement this again, except allowing for more TA flexibility of how to implement, and more systematic classroom observations to capture how students are engaging with the TA, even when they are not necessarily using explicitly the Red Green Yellow Card system as it was intended.

11.2.2 Attitudes in 5BL and 5CL

While this work has outlined successes in 5AL, the first quarter of UCLA's revised IPLS laboratory curriculum, it is of interested to track our students through their complete physics series, and see how we are holistically impacting their perceptions of physics. We have assessment data on these other labs, and so it of interest to characterize how students are maintaining or building upon the critical thinking skill sthey are developing in their first quarter of physics laboratories.

11.3 Assessment of content gains

Here we focus specifically on student gains that are attributable entirely to the structure of the laboratory revisions. At the same time, our laboratory revisions also allowed for us to take student assessment data that can provide holistic feedback regarding student physics conceptual content gains, through their entire quarter of physics lecture, discussion, and laboratory section. In the future, we will have opportunity to revisit assessment data relating to content gains in particular physics subfields. For example, if an instructor is teaching a particular class, like introduction to Electricity & Magnetism (5C), then it may be beneficial to review the learning gains from students in previous quarters of the class, and to then compare one's own learning gains to what has already been measured.

11.4 Next Round of Laboratory Revisions?

While it may seem daunting to think that one must continuously revise curriculum to keep up with the constantly evolving needs of students, there are also manageable aspect of the laboratories, that we can continuously keep tabs on and update as we see reason and opportunity. For example, our online end-of-quarter comprehensive laboratory feedback surveys, which we have been administering since the start of our revisions, offer fantastic feedback regarding student attitudes about particular labs, and even aspects of different laboratory assignments. Such feedback can provide insight as to which laboratory manuals are still unclear, which pre-labs could support students with increased background materials or problem-solving scaffolding, and which laboratory activities are not working entirely as originally designed. One particular improvement that can be made, even this summer, is to review the laboratories and cross-reference the content with the textbook. Given that all students, in any UCLA IPLS course, are now required to use the same textbook, such connection of laboratory background and experiment, to familiar physics principles, could offer additional support to students struggling to make find meaning and value to their labs.

APPENDIX A

A.1 Single Subject Peripheral Acuity Results

In an effort to be transparent about all of our data results, we show the raw data that we collected, one each participant. Participants were either internal lab members who took pilot data on themselves, internal lab members who acted as a participant in a mock study session (practice for the upcoming participant), or participant were IRB-approved, recruited study session participants.

A.1.1 Pilot Data

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0416	.0116	.0029	16	11.7	.185	.243
Fully Crowded, 1D (FC1)	.2945	.0980	.0253	15	6.85	$< .001$	.461
Fully Crowded, 2D (FC2)	.2883	.0642	.0075	73	16.0	$< .001$	.365
PC, center (PCC)	.1425	.0437	.0109	16	9.8	.1773	.5737
PC, outer (PCO)	.0700	.0194	.0049	16	12.2	.0054	.0685
PC, 2x flank (PC2)	.1615	.0302	.0076	16	26.3	.3473	.2909
PC, 3x flank (PC3)	.1740	.0172	.0044	15	97.5	0.002	.3687
PC, 4x flank (PC4)	.1578	.0417	.0120	12	13.1	.073	.699
CC, 1x flank (CC)	.0359	.0092	.0025	14	14.9	$> .5$	.135
CC, 1x flank (CCb)	.0341	.0069	.0018	14	23.8	$> .5$	.138
CC, 4x flank (CC4)	.0314	.0094	.0026	13	10.9	.268	.476

Table A.1: **Single session test statistics, INT1.** This table shows the test statistics calculated for INT1 pilot data, for all given peripheral vision protocols tested.

Pilot data subjects were internal lab members, who took data on themselves throughout the duration of our experiment. Pilot data was taken chronologically before mock session

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0247	.0062	.0015	16	14.8	.002	.799
Isolated Character (ICb)	.0260	.0082	.0021	16	9.2	.355	.489
Fully Crowded, 1D (FC1)	.2200	.1311	.0338	15	2.3	$< .001$	.7145
Fully Crowded, 2D (FC2)	.1775	.0458	.0052	79	13.3	$< .001$	.777
Fully Crowded, 2D (FC2b)	.2118	.0863	.0095	83	5.4	$< .001$	.0893
PC, center (PCC)	.0583	.0239	.0060	16	5.6	$> .5$	.8785
PC, center (PCCb)	.0913	.0249	.0062	16	12.7	.3516	.5235
PC, outer (PCO)	.0453	.0118	.0030	15	13.7	.2683	.2786
PC, outer (PCOb)	.0431	.0214	.0053	16	3.79	.2558	.8586
PC, 2x flank (PC2)	.1035	.0439	.0110	16	5.31	.2930	.6654
PC, 3x flank (PC3)	.1047	.0342	.0086	16	8.9	.4748	.6642
PC, 4x flank (PC4)	.1171	.0265	.0076	12	18.4	$> .5$	.9372
CC, 1x flank (CC)	.0199	.0071	.0019	14	7.5	$> .5$	.3176
CC, 1x flank (CCb)	.0276	.0071	.0019	14	14.9	.4066	.3024
CC, 4x flank (CC4)	.0215	.0038	.0011	12	31.5	.3051	.3139
CC, 4x flank (CC4b)	.0207	.0052	.0014	14	15.1	.1600	.7354
CC, 5x flank (CC5)	.0198	.0053	.0019	8	10.9	$> .5$	.6857

Table A.2: **Single session test statistics, INT2.** This table shows the test statistics calculated for INT2 pilot data, for all given peripheral vision protocols tested.

and study session were completed, so, in general, there is a wider variety of pilot data than either mock data or study session data. Additionally, internal subjects, in their pilot data, spanned a greater percentage of the variety of visual stimuli. As result, particular cross comparisons across diverse peripheral vision study session paradigms was often able to be analyzed for internal data, and not mock sessions or study sessions.

Internal lab members became mock session participants in the case where a final protocol with subject script needed to be tested before lab members performed the study session with

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0317	.0062	.0033	16	5.3	.3498	.3978
Fully Crowded, 2D (FC2)	.2756	.1171	.0132	79	4.6	$< .001$	.7002
PC, center (PCC)	.1091	.0247	.0064	15	18.6	$> .5$	.6454
PC, outer (PCO)	.0729	.0186	.0046	16	14.3	.2944	.5046
PC, 2x flank (PC2)	.1249	.0295	.0074	16	16.7	$> .5$	.7209
PC, 3x flank (PC3)	.1072	.0183	.0046	16	31.9	$> .5$	.4584
CC, 1x flank (CC)	.0236	.0078	.0021	14	8.79	$> .5$	.8316
CC, 1x flank (CCb)	.0366	.0067	.0018	14	29.0	$> .5$	.3345
CC, 4x flank (CC4)	.0274	.0084	.0022	14	10.3	.0955	.0350

Table A.3: **Single session test statistics, INT3.** This table shows the test statistics calculated for INT3 pilot data, for all given peripheral vision protocols tested.

the real study participants. Multiple mock sessions were done for each peripheral vision study session stimulus, so that a variety of lab members were able to be trained to run the study during upcoming participant study sessions.

Study session data was the IRB-approved external participant results. Unfortunately, due to the COVID-19 outbreak, we were not able to recruit nearly as many participant as we had planned for. As such, we report not only our participant results but also our internal and mock session results as well.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0235	.0099	.0025	16	5.14	.1719	.8239
Isolated Character (ICb)	.0377	.0144	.0036	16	6.25	.0861	.4253
Fully Crowded, 2D (FC2)	.2758	.1199	.0130	85	4.15	$< .001$	.9277
PC, center (PCC)	.0937	.0323	.0081	16	7.77	.0433	.6454
PC, center (PCCb)	.0861	.0358	.0092	15	5.42	$< .001$	.9347
PC, outer (PCO)	.0567	.0245	.0061	16	4.92	.1239	.6448
PC, inner (PCI)	.0784	.0214	.0053	16	12.5	.3731	.1237
PC, 2x flank (PC2)	.1197	.0287	.0074	15	16.5	.2710	.1304
PC, 3x flank (PC3)	.1041	.0346	.0086	16	8.45	.1088	.9591
PC, 4x flank (PC5)	.1175	.0275	.0069	12	16.8	2099	.9591
CC, 1x flank (CC)	.0273	.0091	.0024	14	8.77	2114	.9289
CC, 4x flank (CC4)	.0400	.0181	.0283	12	4.94	.0045	.1797
CC, 5x flank (CC5)	.0273	.0098	.0031	10	7.99	$> .5$	.5476

Table A.4: **Single session test statistics, INT4.** This table shows the test statistics calculated for INT4 pilot data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0322	.0113	.0027	17	7.47	.0222	.9819
Fully Crowded, 2D (FC2)	.2474	.0675	.0087	60	11.9	$< .001$	.4639
PC, center (PCC)	.0634	.0145	.0036	16	17.8	3979	.9382
PC, outer (PCO)	.0492	.0154	.0039	15	9.45	.0296	.0990
PC, 4x flank (PC4)	.0695	.0163	.0047	12	16.6	$> .5$	.3312
CC, 1x flank (CC)	.0245	.0105	.0028	14	5.27	.2731	.8048
CC, 4x flank (CC4)	.0252	.0068	.0018	12	13.2	.2876	.8048

Table A.5: **Single session test statistics, INT5.** This table shows the test statistics calculated for INT5 pilot data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0321	.0119	.0030	16	6.70	.1943	.4418
Isolated Character (ICb)	.0339	.0130	.0032	17	6.16	.3848	.8007
Fully Crowded, 1D (FC1)	.2175	.0630	.0168	14	9.76	.0091	.6620
Fully Crowded, 2D (FC2)	.2609	.0388	.0084	72	10.8	< .001	.1814
PC, center (PCC)	.1218	.0423	.0106	16	6.52	0182	.9789
PC, outer (PCO)	.1022	.0118	.0097	16	13.7	.4177	.6657
PC, outer (PCI)	.0713	.0265	.0066	16	6.70	.2780	.6454
PC, 2x flank (PC2)	.1577	.0426	.0106	16	12.7	.> .5	.3282
PC, 3x flank (PC3)	.1509	.0452	.0113	16	10.4	.2795	.0482
PC, 5x flank (PC5)	.1473	.0428	.0107	16	10.7	.3510	.6454
CC, 1x flank (CC)	.0319	.0098	.0026	14	10.2	.0294	.0565
CC, 1x flank (CCb)	.0276	.0077	.0021	14	12.4	> .5	.5594
CC, 4x flank (CC4)	.0359	.0146	.0042	12	6.07	.0890	.6667
CC, 4x flank (CC4b)	.0285	.0063	.0017	14	19.7	> .5	.0198
CC, 5x flank (CC5)	.0391	.0160	.0160	10	6.19	.2085	.1508

Table A.6: **Single session test statistics, INT6.** This table shows the test statistics calculated for INT6 pilot data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0330	.0121	.0030	16	6.71	.0337	.7793
Fully Crowded, 2D (FC2)	.3561	.0911	.0104	76	11.7	< .001	.0529
CC, 1x flank (CC)	.0301	.0100	.0027	14	8.80	> .5	.0181
CC, 4x flank (CC4)	.0315	.0058	.0016	14	28.4	.2976	.8741

Table A.7: **Single session test statistics, INT7.** This table shows the test statistics calculated for INT7 pilot data, for all given peripheral vision protocols tested.

A.1.2 Mock Sessions

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0368	.0127	.0032	16	7.71	.0523	.0974
Fully Crowded, 2D (FC2)	.2972	.1201	.0140	74	4.65	$< .001$	.1936

Table A.8: **Single session test statistics, MOCK1 .** This table shows the test statistics calculated for MOCK1 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0426	.0092	.0024	15	20.2	.3006	.3910
Fully Crowded, 2D (FC2)	.3575	.1325	.0146	82	14.7	$< .001$	.7183

Table A.9: **Single session test statistics, MOCK2 .** This table shows the test statistics calculated for MOCK2 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0267	.0091	.0023	15	8.12	.4556	.2915
Isolated Character (ICb)	.0277	.0053	.0014	15	25.5	$< .001$	.5537
Isolated Character (ICc)	.0291	.0101	.0025	16	7.59	.3135	.5887
Isolated Character (ICd)	.0312	.0126	.0032	16	5.65	.0189	.9395
Fully Crowded, 2D (FC2)	.2496	.0761	.0086	79	8.67	$< .001$	.0615
Fully Crowded, 2D (FC2b)	.2765	.1323	.0259	26	3.74	$< .001$	.7895
PC, center (PCC)	.0860	.0423	.0073	15	8.68	$> .5$	.3975
PC, outer (PCO)	.0737	.0118	.0078	16	5.12	$> .5$	.1110
CC, 1x flank (CC)	.0300	.0138	.0034	16	4.23	.0204	.4859
CC, 4x flank (CC4)	.0309	.0132	.0033	16	4.95	.0441	.3680

Table A.10: **Single session test statistics, MOCK3.** This table shows the test statistics calculated for MOCK3 pilot data, for all given peripheral vision protocols tested.

A.1.3 Study Sessions

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0364	.0089	.0023	15	15.8	.0313	1.00
Fully Crowded, 2D (FC2)	.2919	.0535	.0064	70	23.0	$< .001$	.4240

Table A.11: **Single session test statistics, SUB1 .** This table shows the test statistics calculated for SUB1 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0450	.0171	.0043	16	6.34	.0148	.8163
Fully Crowded, 2D (FC2)	.3267	.0964	.0106	82	9.05	$< .001$	.9643

Table A.12: **Single session test statistics, SUB2 .** This table shows the test statistics calculated for SUB2 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0530	.0108	.0026	17	21.8	.0016	.5575
Fully Crowded, 2D (FC2)	.3299	.1037	.0120	75	8.09	$< .001$	.8426

Table A.13: **Single session test statistics, SUB3.** This table shows the test statistics calculated for SUB3 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0369	.0213	.0053	16	2.79	.1118	.0030
Fully Crowded, 2D (FC2)	.2950	.1081	.0128	71	5.95	$< .001$	.2376

Table A.14: **Single session test statistics, SUB4.** This table shows the test statistics calculated for SUB4 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0243	.0094	.0024	16	6.10	$> .5$	.4255
Fully Crowded, 2D (FC2)	.3209	.1153	.0136	72	6.07	$< .001$	.0467

Table A.15: **Single session test statistics, SUB5.** This table shows the test statistics calculated for SUB5 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0417	.0136	.0033	17	8.59	2998	.4914
Fully Crowded, 2D (FC2)	.3077	.1159	.0132	77	5.65	$< .001$	1.00

Table A.16: **Single session test statistics, SUB6.** This table shows the test statistics calculated for SUB6 study session data, for all given peripheral vision protocols tested.

VISUAL PARADIGM	$< \frac{dLH}{dE} >$	SD	SEM	N	χ^2_ν	p-normal	p-RL same
Isolated Character (IC)	.0348	.0132	.0032	17	6.33	$> .5$	.0975
PC, center (PCC)	.0856	.0267	.0067	16	9.65	$> .5$	.2050
PC, outer (PCO)	.1166	.0522	.0135	15	4.81	.1730	.1304

Table A.17: **Single session test statistics, SUB7.** This table shows the test statistics calculated for SUB7 pilot data, for all given peripheral vision protocols tested.

A.2 Multi-subject comparisons, across crowding paradigm

As a control, we compared our results, for each visual crowding peripheral vision paradigm, across our diverse participant population. In this way, we can show that there is not strong systematic difference of results across our internal data, mock session data, and participant study session results. Figure A.1 shows Normalized threshold letter height ratios, across all of our fully crowded peripheral vision study session blocks, categorized by type of experimental data session. Figure A.2 shows Normalized threshold letter height ratios, across all of our peripheral crowded vision study session blocks, categorized by experimental data session. Figure A.3 shows Normalized threshold letter height ratios, across all of our center crowded vision study session blocks, categorized by experimental data session.

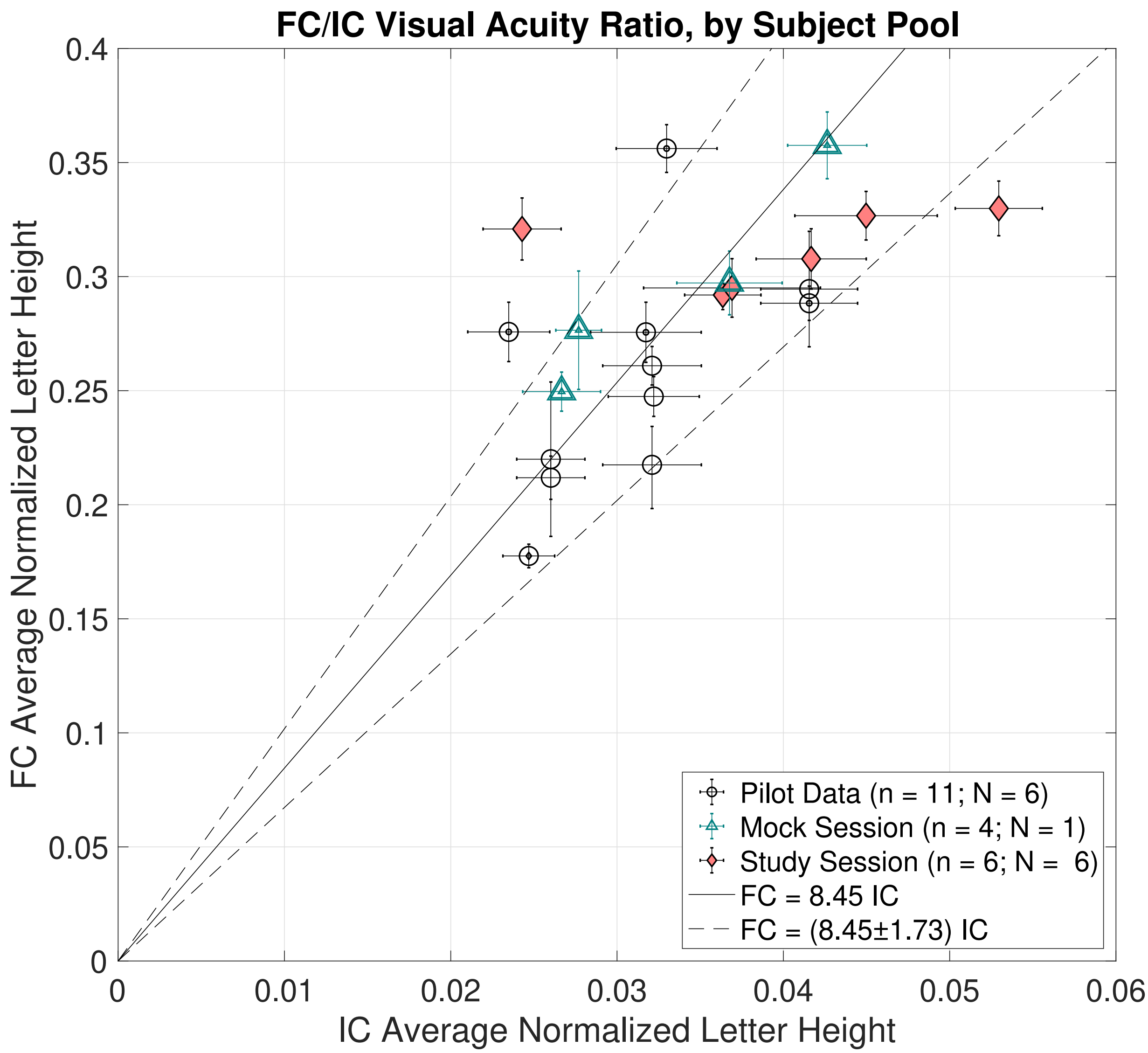


Figure A.1: **Normalized threshold LH ratios, comparing subject pool across FC trials.** This plot shows normalized threshold letter height ratios across all subject FC trials, comparing pilot data, mock sessions, and study session results. Black circles with a solid center dot represent pilot sessions where the Isolated Character control run was taken on the same day as the experimental crowding paradigm. Turquoise triangles with a solid center dot represent mock sessions where the Isolated Character control run was taken on the same day as the experimental crowding paradigm. All study sessions had IC control data taken on the same day as the experimental crowding paradigm session.

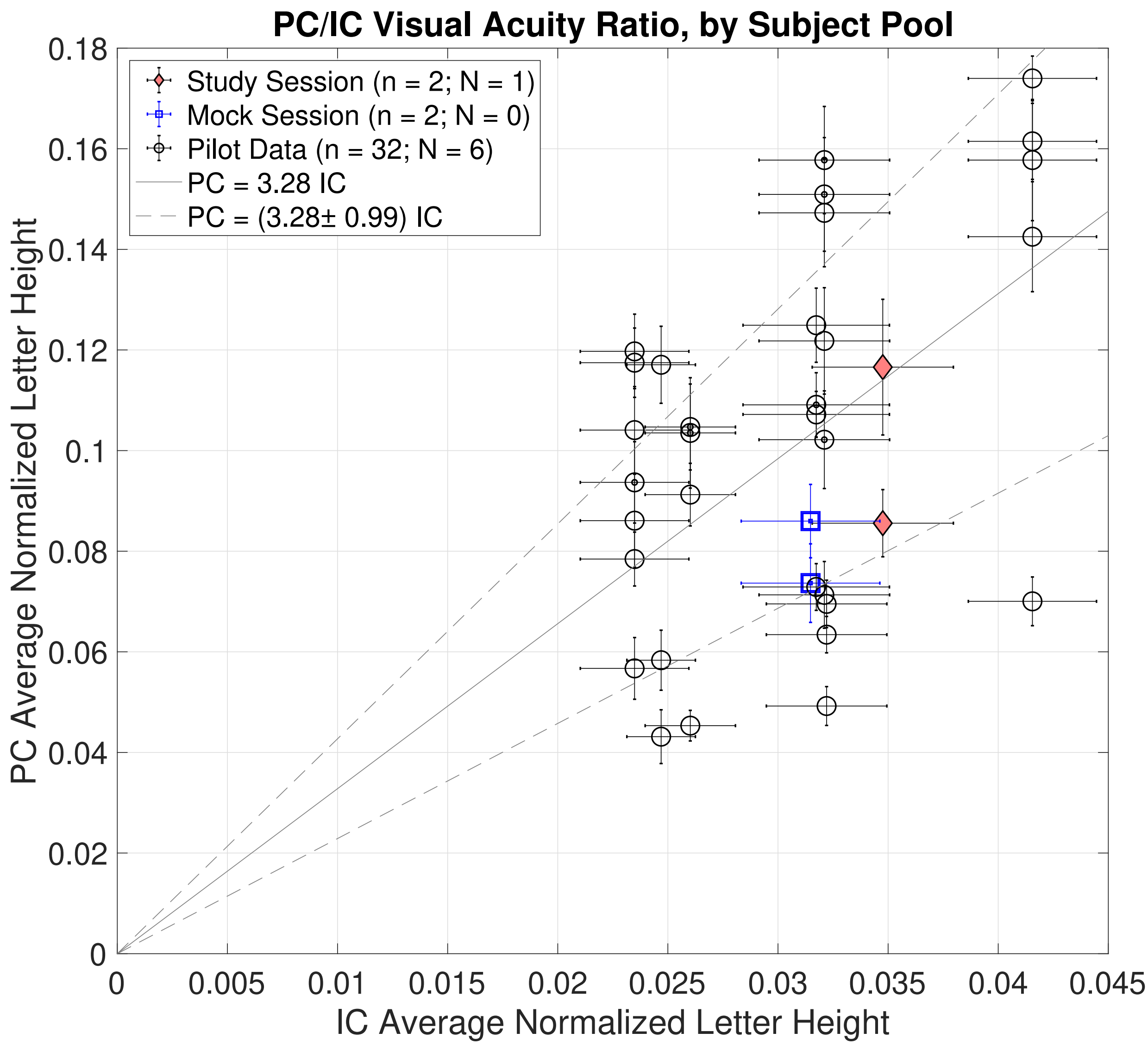


Figure A.2: **Normalized threshold LH ratios, comparing subject pool across PC trials.** This plot shows normalized threshold letter height ratios across all subject PC trials, comparing pilot data, mock sessions, and study session results. Black circles with a solid center dot represent pilot sessions where the Isolated Character control run was taken on the same day as the experimental crowding paradigm. Blue squares with a solid center dot represent mock sessions where the Isolated Character control run was taken on the same day as the experimental crowding paradigm. All study sessions had IC control data taken on the same day as the experimental crowding paradigm session.

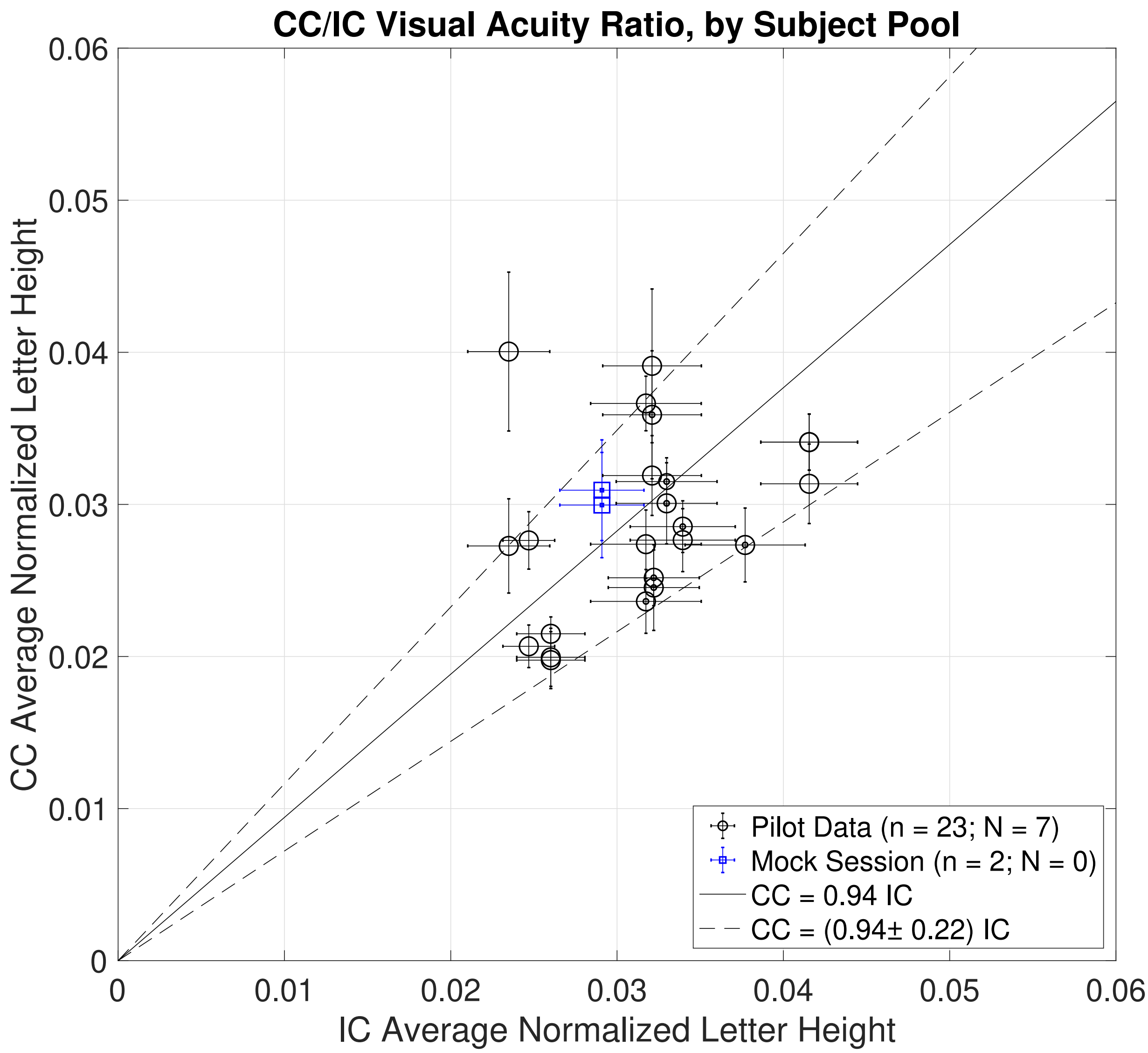


Figure A.3: **Normalized threshold letter height ratios, comparing subject pool across CC trials.** This plot shows normalized threshold letter height ratios across all subject CC trials, comparing pilot data, mock sessions, and study session results. Black circles with a solid center dot represent pilot sessions where the Isolated Character control run was taken on the same day as the experimental crowding paradigm. Blue squares with a solid center dot represent mock sessions where the Isolated Character control run was taken on the same day as the experimental crowding paradigm.

A.3 V1 Simulation Results

Additional simulation results are shown in Figure A.4, whereby the center gaze (or center of attention vector) is on the vertical line edge of the letter. In this case, it can be seen that there is a very interesting at best, and pathological case at worst, which occurs in the brain's internal representation. In this unique circumstance, it appears that the representation is not entirely scale-invariant. While the right visual field representation is preserved in a scale-invariant way on the left hemisphere of the brain, the vertical line of the "P" is problematic in that it is exactly in the center visual field and is represented by both the left and right hemisphere of the brain. Given this situation, we have reason to believe that the visual gaze vector (and therefore visual attention vector) moves to focus on an *empty* space either in the *center* of the letter or next to the letter. We do not that think that the brain centers on information-heavy lines, because if the important information is exactly dead-center then it does not map congruently onto the log-polar transformation from visual field to internal cortical hemispheric representation along the semantic-visual processing pathway of the brain.

Figure A.5 shows the internal brain representation that is scale-invariant, when the center gaze (or attention vector) is focused in the center of the empty space within the letter "P." At the same time, we acknowledge that there is not necessarily a single, unique semantic representation of the letter "P" *across* different humans, given that the "center" location for the letter may be slightly different, depending on the location of the gaze for the initial semantic learning. For example, Figure A.6 shows an equivalent scale-invariant semantic representation for the letter "P" when the center gaze (or visual attention vector) is slightly offset from the center of the hole inside the letter. Such a representation would work equally well, except that there would be a slightly different specific neuronal firing within the brain, that would cause a match with the semantic representation, for that particular person. Each person would be able to "learn" their own semantic representation within the brain, given that their eyes would focus (and their attention vector would focus) on a particular location of the hole either inside or around a given character. Such a model for semantic representation could also be expanded to explain how humans make sense of groups of characters into words.

Lastly, Figure A.7 shows how such scale invariance only holds when the relative "center" is fixed. When the position of the letter translates, with respect to that "center" location, then scale invariance is lost, and there can no longer be a single representation of neuron activation in the brain that serves for all object locations. This is rationale for why it is helpful for the brain to make an internal translation, such that the semantic properties of the letter can be extractd, *as if* the object had been located at the center of the visual field, from the very beginning.

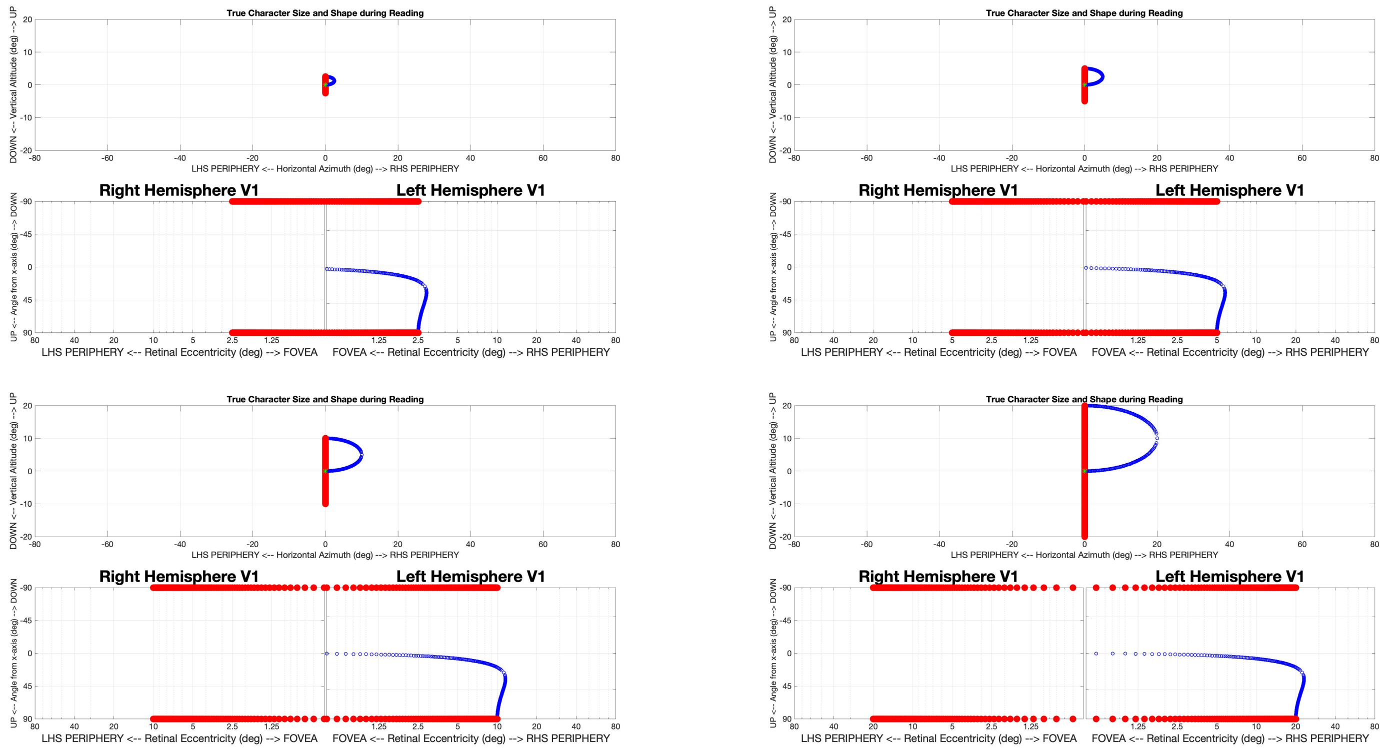


Figure A.4: Model showing letter “P” neuronal activation in the primary visual cortex, given that the gaze is centered at the point where the greatest number of lines intersect, the most crowded part of the extended object. Moving from the top image, downwards, the size of the object in the visual field increases as the gaze remains fixed. While the curved portion of the letter in the right visual field remains constant shape and merely translates the neuronal activity in V1, the large portion of points in the center of the visual field active a large portion of V1, on both sides, and are not scale invariant under object dilation. Such modeling supports the idea that we do not fix the center of our gaze directly at the highest density of an object, and instead, focus our gaze at the empty space between strokes of a character.

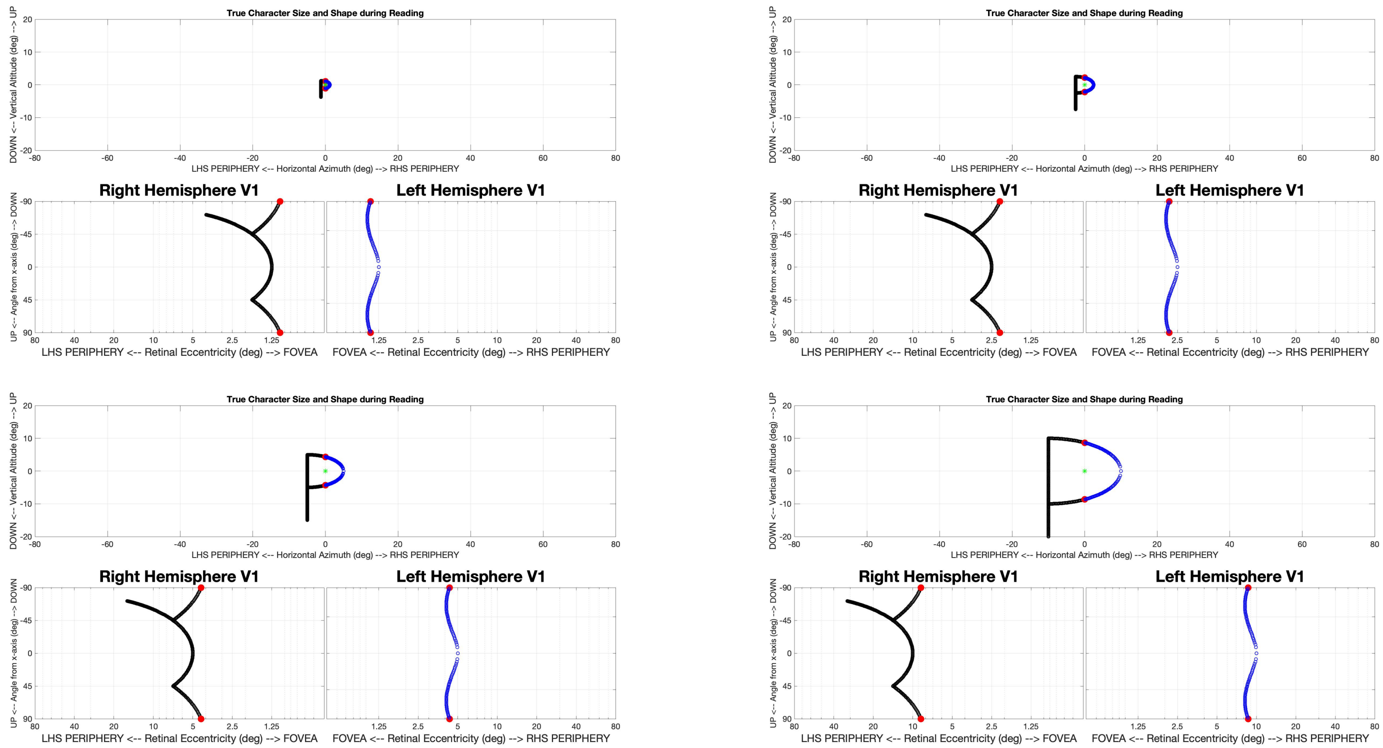


Figure A.5: Model showing letter “P” neuronal activation in the primary visual cortex, given that the gaze is centered in the empty space within the letter, the the least crowded part of the extended object. Moving from the top image, downwards, the size of the object in the visual field increases as the gaze remains fixed. Throughout the entire dilation of this object, the represented shape and size on V1 remains absolutely constant. The size of the object is encoded merely by the translational shift, whereby both left and right sides of the primary visual cortex retain their own specific and consistent contribution to the semantic identify of the character. Such modeling supports the idea that we do not fix the center of our gaze directly at the highest density of an object, and instead, focus our gaze at the empty space between strokes of a character.

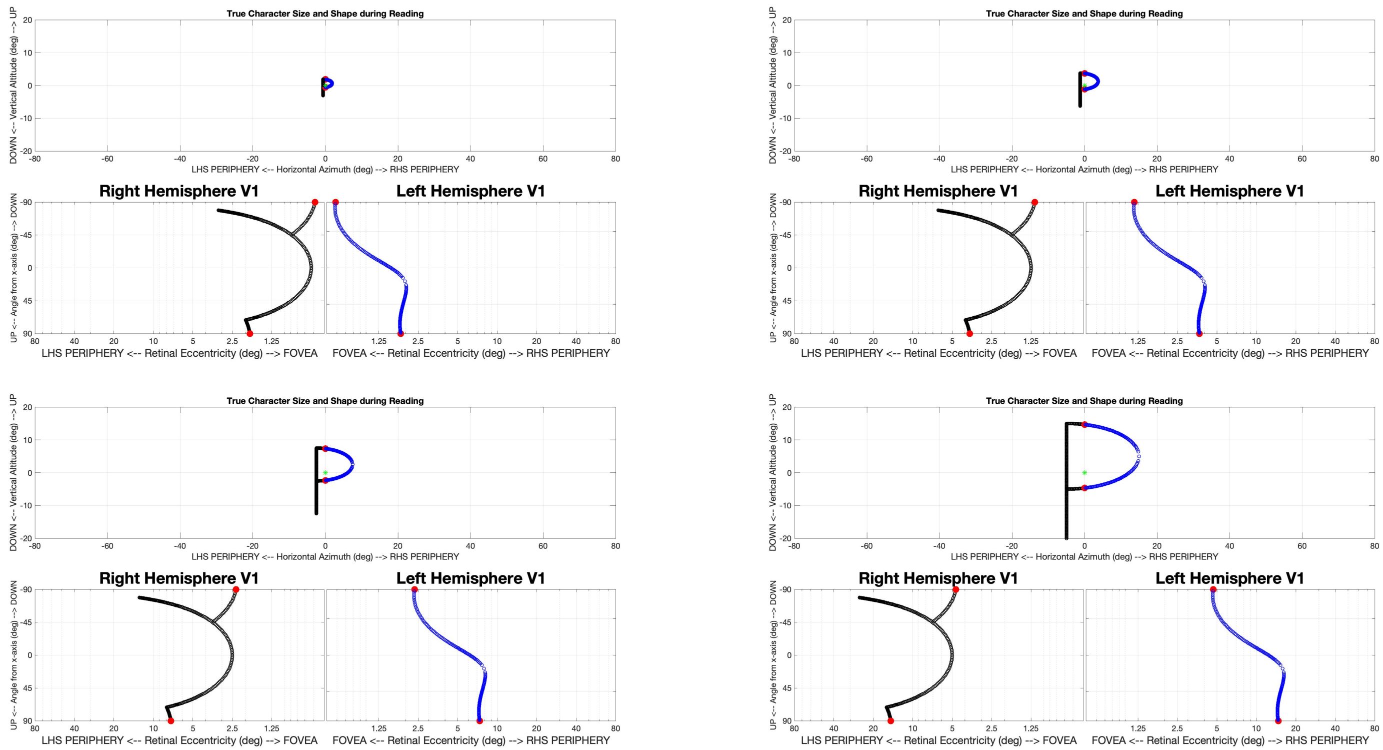


Figure A.6: Model showing letter “P” neuronal activation in the primary visual cortex, given that the gaze is slightly off-centered from the empty space in the letter. Moving from the top image, downwards, the size of the object in the visual field increases as the gaze remains fixed. Depending on exactly where the center gaze is located, even inside the letter empty space, there is a slightly different pattern of neuron activation, that defines the form.

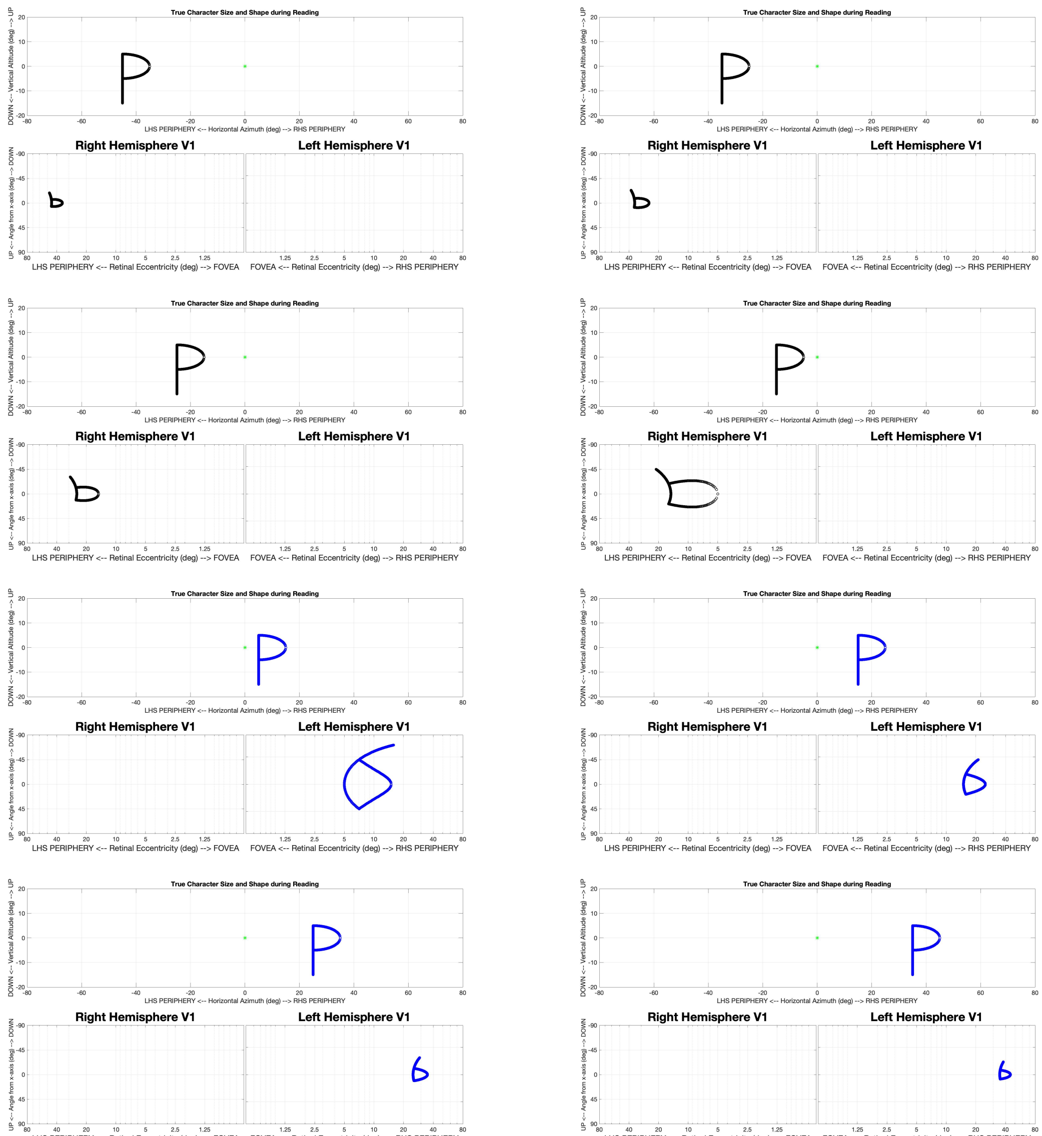


Figure A.7: Translation of letter “P” across the screen, ranging from high retinal eccentricities to near-center positions. While the peripheral representation of the letter preserves the edges and general form (reflection of the image), this is not how the character is represented in our brain when it is in our center gaze. If the brain does not ”remap” this peripheral representation in some way, then it would require our brain to recognize many different independent patterns for the same object.

For the simulation results involving comparing letter "E" and letter "B" confusions, results were compared to single-eye peripheral vision tests performed by Reich et al. published in 2000. Using the data shown in Figure A.8, Figure A.9, Figure A.10, and Figure A.11, it is shown that such confusions maximally occur when the letter is shown on leftwards peripheral location, as opposed to a central location, a downwards peripheral location, or a lower-left peripheral location.

The "confusion" correlation parameter was calculated in their work, by quantifying the percentage of the time that a participant confused the letter "E" for the letter "B," and adding that to the percentage of the time that a participant confused the letter "B" for the letter "E," in their given visual stimulus presentation protocol. The number of confusions was normalized by the number of presentations, so that a "confusion index" ranging from 0.00 to 1.00 could be quantified for each pair of letters. They calculated these letter confusion indices for each letter combination, across four different visual field locations: center, left periphery, bottom (lower) periphery, and lower-left periphery. Interestingly, the confusion co-efficient for "E" and "B" letter pairs is largest, in the condition where the letters were presented to the left periphery (confusion index = .16), which they found to be statistically significant. However, when the letters were presented in center vision, the confusion index was at its lowest value (confusion index = .03), and was not found to be statistically significant. Additionally, when the letter was presented in the periphery, but a vertical peripheral location or a mixture of vertical and horizontal location, the confusion index between the letter "B" and the letter "E" was found to be less then that for the entirely horizontal peripheral presentation. This suggests that the most critical aspect fo the confusion of the two letters arises from the brain needing to process a different between the two letters that is related to a horizontal displacement from the center. As such, we focused our simulation efforts on this: to show why this primarily horizontal confusion can be explained through our simulation of the visual attention vector overshoot. Of course, it would be helpful to do additional tests, using the participant's left eye, and presenting the letter in the right visual field. This is part of our future work plans.

A

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
B	.03																							
C	.02	.03																						
D	.00	**.10**	**.09**																					
E	.02	.03	**.11**	.04																				
F	.03	**.01**	.00	.01	.03																			
G	.02	.05	.07	.04	.04	.00																		
H	**.01**	.00	.02	.01	.00	.00	.00																	
J	.02	**.01**	.03	.00	**.01**	.04	.00	.02																
K	**.10**	.03	.05	.01	.05	.02	.04	.02	.02															
L	.06	.00	.02	.00	.00	.00	.00	.00	.00	.02														
M	.06	.00	.00	.00	.02	.00	.00	**.22**	.00	.01	.00													
N	.01	.03	.03	.01	.00	.01	.01	**.12**	.00	.04	.01	**.10**												
O	.02	.01	**.17**	**.16**	.01	.00	**.09**	.03	**.01**	.00	.00	.00	.05											
P	.05	.07	.03	**.09**	.05	**.33**	.03	.03	.02	.03	.00	.01	.03	.05										
Q	.05	.00	**.09**	.07	.01	.00	**.22**	.02	.01	**.01**	.00	.00	.03	**.17**	**.10**									
R	.04	.04	.04	.00	.02	.00	.02	.04	.02	**.10**	.00	**.09**	.02	.01	**.12**	.01								
S	.04	**.13**	.08	.05	**.09**	.01	**.31**	.01	.02	.02	.00	.01	.04	.08	.01	.06	.04							
T	.02	.02	.03	.01	.03	.03	.03	.01	.02	.02	**.01**	**.01**	.02	.03	.03	.00	.01	**.01**						
U	.02	.03	.03	.04	.02	.02	.02	.03	.07	.01	.02	.00	.03	.06	.02	.02	.00	**.01**	.02					
V	.01	.01	.02	.00	.00	.00	.01	.00	.05	.02	**.01**	.03	**.01**	.02	.00	.01	.01	.03	.07	.04				
W	.03	.01	.02	.00	.00	.00	.00	.03	.06	.03	.00	.04	.02	.01	.02	.00	.01	**.01**	.05	.08	**.16**			
X	.07	.00	.03	.00	.02	.00	.00	.00	.05	.08	.03	.02	.02	.01	.00	.00	.00	.03	.02	.00	.04	.02		
Y	.02	.01	.03	.00	.02	.01	.00	.01	.02	.00	.02	.01	.00	.02	.03	.03	.03	.03	**.20**	.03	**.20**	.05	.08	
Z	.04	.00	.03	**.01**	.03	.03	.02	.00	.03	**.01**	.00	.01	**.01**	.01	.02	.01	.00	.03	.03	.00	.00	.02	.06	.03

Figure A.8: textbf“E” vs. “B” letter confusion correlation chart, center vision. This chart shows letter confusion correlations for all combinations of uppercase letters, whereby the stimulus was shown in the center visual field, as viewed singly by the right eye of the participant. Adapted from Reich and Bedell (2000).

B

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
B	.02																							
C	.00	.00																						
D	.00	**.16**	.02																					
E	.00	**.16**	.00	.00																				
F	.00	.00	.00	.00	.07																			
G	.00	**.09**	**.20**	.02	**.16**	.02																		
H	.00	.00	.00	.00	.00	.00	.00																	
J	.02	.00	.00	.02	.00	.00	.00	.00																
K	.02	.00	.00	.00	.00	.00	.00	.00	.02															
L	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00														
M	.00	.00	.00	.02	.00	.00	.00	**.13**	.00	.02	.00													
N	.00	.02	.00	.00	.00	.00	.00	**.13**	.00	.00	.00	**.18**												
O	.02	.00	.07	**.11**	.00	.02	**.11**	.00	.00	.00	.00	.00	.00											
P	.00	.02	.00	.02	.02	**.20**	.00	.00	.02	.04	.00	.00	.02	.07										
Q	.00	.00	**.09**	**.09**	.00	.02	.13	.00	.00	.00	.00	.00	.00	**.38**	.00									
R	.00	.07	.00	.04	.00	.02	.04	.02	.00	.02	.00	.07	.00	.02	.02	.00								
S	.00	**.16**	**.09**	.04	**.09**	.00	.16	.00	.00	.00	.00	.00	.00	.04	.04	.02	.00							
T	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00						
U	.00	.00	.00	.00	.00	.00	.02	.07	.07	.00	.02	.00	.02	.00	.00	.00	.02	.02	.00					
V	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00				
W	.00	.00	.00	.00	.00	.00	.00	.04	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	**.09**	**.16**			
X	.00	.00	.00	.00	.00	.02	.00	.00	.02	**.11**	.00	.00	.00	.02	.00	.00	.02	.02	.00	.02	.00	.02		
Y	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.00	.02	.00	.00	.00	**.13**	.00	**.16**	.04	.02	
Z	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.02	.00	.00	.00	.00	.00

Figure A.9: textbf"E" vs. "B" letter confusion correlation chart, center vision. This chart shows letter confusion correlations for all combinations of uppercase letters, whereby the stimulus was shown in the left visual field, as viewed singly by the right eye of the participant. Adapted from Reich and Bedell (2000).

C

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
B	.00																							
C	.02	.00																						
D	.00	**.13**	.07																					
E	.02	**.11**	**.09**	.00																				
F	.02	.02	.02	.00	.02																			
G	.04	**.22**	**.24**	.00	.07	.00																		
H	.00	.00	.00	.00	.00	.02	.00																	
J	.02	.00	.00	.00	.00	.00	.00	.00																
K	.02	.02	.02	.00	.02	.04	.00	.02	.00															
L	.02	.00	.02	.00	.00	.00	.00	.02	.00	.00														
M	.00	.07	.00	.02	.00	.00	.00	**.13**	.00	.07	.04													
N	.00	.04	.00	.00	.00	.00	.00	**.11**	.00	.00	.00	**.11**												
O	.00	.00	**.13**	**.20**	.04	.00	**.18**	.00	.02	.00	.00	.00	.00											
P	.00	.02	.02	.02	.02	**.24**	.04	.02	.00	.02	.00	.04	.02	.00										
Q	.00	.00	**.16**	.07	.02	.02	**.16**	.00	.00	.00	.02	.00	.00	**.31**	.00									
R	.02	.04	.02	.02	.00	.02	.07	**.11**	.00	.02	.00	**.11**	**.13**	.04	.02	.07								
S	.00	**.29**	**.20**	.00	**.20**	.02	**.13**	.00	.00	.00	.00	.02	.00	**.11**	.07	.02	.00							
T	.00	.02	.02	.00	.00	.02	.00	.04	.00	.00	.04	.07	.04	.00	.02	.00	.02	.02						
U	.00	.04	.00	**.09**	.00	.00	.02	**.09**	**.16**	.00	.02	**.09**	.00	.00	.02	.02	.00	.00	.00					
V	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.00	.00	.02	.00	.00	.02	.02	.00				
W	.02	.02	.00	.00	.00	.00	.00	.00	.04	.02	.02	.02	.02	.00	.02	.00	.00	.00	.02	**.18**	**.31**			
X	.07	.00	.02	.00	.00	.02	.02	.00	.00	**.11**	.00	.00	.00	.04	.00	.00	.00	.00	.02	.00	.02	.02		
Y	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.00	.00	.00	.00	.04	.00	.02	.00	.04	.00	**.27**	.04	**.13**	
Z	.00	.00	.02	.00	.00	.02	.00	.00	.00	.00	.00	.00	.00	.02	.04	.00	.00	.04	.04	.00	.00	.00	**.09**	.00

Figure A.10: textbf“E” vs. “B” letter confusion correlation chart, center vision. This chart shows letter confusion correlations for all combinations of uppercase letters, whereby the stimulus was shown in the lower visual field, as viewed singly by the right eye of the participant. Adapted from Reich and Bedell (2000).

D

	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
B	.02																							
C	.00	.00																						
D	.00	.07	.02																					
E	.00	.07	.02	.02																				
F	.00	.00	.04	.00	.04																			
G	.00	**.18**	**.27**	.02	.07	.00																		
H	.00	.02	.02	.02	.00	.04	.02																	
J	.00	.00	.00	.02	.00	.00	.00	.00																
K	.04	.00	.07	.00	.07	.00	.02	.00	.00															
L	.02	.00	.00	.00	.00	.02	.00	.02	.02	.00														
M	.02	.04	.00	.02	.00	.02	.02	**.18**	.02	**.11**	.00													
N	.02	.02	.00	.00	.00	.00	.02	**.20**	.00	.04	.00	**.13**												
O	.00	.02	**.24**	**.09**	.00	.00	**.11**	.00	.00	.02	.00	.00	.00											
P	.02	.00	.02	.07	.07	**.24**	.02	.02	.00	.04	.00	.02	.04	**.09**										
Q	.04	.00	**.16**	.02	.02	.00	**.24**	.00	.02	.00	.00	.00	.00	**.36**	.00									
R	.02	.07	.02	**.16**	.00	.04	**.13**	.00	.00	**.13**	.00	**.09**	.02	.04	.07	.00								
S	.00	**.13**	**.13**	.00	**.18**	.00	.07	.00	.00	.02	.02	.00	.00	**.09**	.00	**.11**	**.09**							
T	.00	.00	.00	.00	.02	.00	.00	.02	.00	.00	.00	.04	.00	.00	.00	.02	.00	.02						
U	.00	.02	.04	.04	.00	.00	.02	**.11**	.02	.00	.04	.07	**.13**	.02	.00	.02	.00	.02	.00					
V	.00	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.07	.00				
W	.02	.02	.00	.02	.00	.00	.02	.02	**.11**	.04	.00	.04	.07	.02	.02	.00	.00	.04	.04	**.13**	**.18**			
X	.07	.00	.02	.00	.00	.00	.02	.00	.02	.07	.02	.00	.02	.00	.00	.00	.00	.00	.04	.02	.04	.02		
Y	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	**.11**	.00	**.24**	.04	**.09**	
Z	.00	.02	.02	.00	.04	.07	.00	.00	.00	.04	.00	.02	.00	.00	.07	.02	.04	.02	**.13**	.00	.00	.00	.02	.02

Figure A.11: textbf"E" vs. "B" letter confusion correlation chart, center vision. This chart shows letter confusion correlations for all combinations of uppercase letters, whereby the stimulus was shown in the lower-left visual field, as viewed singly by the right eye of the participant. Adapted from Reich and Bedell (2000).

B.4 Laboratory Revisions E-CLASS Attitude Results

In an effort to show all of our experimental results, we present our statistics and raw histogram data, for each quarter of UCLA's IPLS mechanics laboratory, along with the pre-revisions and post-revisions quarter of the second IPLS laboratory in the series. To start, comprehensive statistics are shown for the means and medians of the pre quarter, post quarter and during quarter shift student attitudes, for the three attitude questions analyzed in this study. Additionally, to test statistical significance, the sign-test results are also shown.

While particular quarters' results are explicitly referenced, with data shown in the results section, we also show here histogram results for *every* quarter of our revised laboratory. Results for the three attitude questions, "Asking Own Questions," "Asking Instructor for Help," and "Blindly Following Instructions," are presented for every quarter of the laboratory reviewed in this study.

B.4.1 Comprehensive Statistics

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.17	3.51	2.26
PostQ Mean	3.53	3.49	2.30
QShift Mean	0.36	-0.022	0.046
PreQ Median	3	4	2
PostQ Median	4	4	2
QShift Median	0	0	0
Sign Test p-value	2.4e-9	0.90	0.71
Sign Test ΔS	95	129	126

Table B.18: **Attitude Test Statistics, 5AL 17F**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 457.

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.03	3.63	2.43
PostQ Mean	3.60	3.57	2.31
QShift Mean	0.57	-0.056	0.13
PreQ Median	3	4	2
PostQ Median	4	4	2
QShift Median	0	0	0
Sign Test p-value	1.9e-14	0.31	0.036
Sign Test ΔS	46	88	104

Table B.19: **Attitude Test Statistics, 5AL 18W**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 305.

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.011	3.46	2.57
PostQ Mean	3.45	3.39	2.50
QShift Mean	0.44	–0.071	0.071
PreQ Median	3	4	2
PostQ Median	4	4	2
QShift Median	0	0	0
Sign Test p-value	5.2e-8	0.30	0.36
Sign Test ΔS	39	62	66

Table B.20: **Attitude Test Statistics, 5AL 18S**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N =212.

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.03	3.60	2.53
PostQ Mean	3.52	3.37	2.58
QShift Mean	0.50	-0.23	0.043
PreQ Median	3	4	2
PostQ Median	4	4	2
QShift Median	0	0	0
Sign Test p-value	4.1e-12	1.0e-04	0.61
Sign Test ΔS	64	125	92

Table B.21: **Attitude Test Statistics, 5AL 18F**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 350.

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.07	3.56	2.65
PostQ Mean	3.72	3.26	2.56
QShift Mean	0.64	-0.30	0.091
PreQ Median	3	4	2
PostQ Median	4	3.5	2
QShift Median	1	0	0
Sign Test p-value	2.2e-16	0.0033	0.7598
Sign Test ΔS	29	99	88

Table B.22: **Attitude Test Statistics, 5AL 19W**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 274

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.08	3.68	2.59
PostQ Mean	3.63	3.52	2.52
QShift Mean	0.55	-0.16	-0.071
PreQ Median	3	4	2
PostQ Median	4	4	2
QShift Median	1	0	0
Sign Test p-value	6.8e-10	0.14	0.49
Sign Test ΔS	42	77	72

Table B.23: **Attitude Test Statistics, 5AL 19S**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 239.

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	3.34	3.46	2.46
PostQ Mean	3.46	3.43	2.46
QShift Mean	0.12	-0.026	0.0060
PreQ Median	3	4	2
PostQ Median	4	4	2
QShift Median	0	0	0
Sign Test p-value	0.046	0.95	0.61
Sign Test ΔS	128	134	129

Table B.24: **Attitude Test Statistics, 5BL 18F**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 497.

Test Statistic	Own Questions	Need Help	Follow Instructions
PreQ Mean	2.80	3.39	2.57
PostQ Mean	2.91	3.11	2.63
QShift Mean	0.11	-0.28	0.063
PreQ Median	3	4	2
PostQ Median	3	3	2
QShift Median	0	0	0
Sign Test p-value	0.14	0.00062	0.85
Sign Test ΔS	51	82	58

Table B.25: **Attitude Test Statistics, 6BL 17F**. Pre quarter, post quarter, quarter shifts, and p-values are shown for all three E-CLASS questions assessed. N = 223.

B.4.2 Asking Own Questions

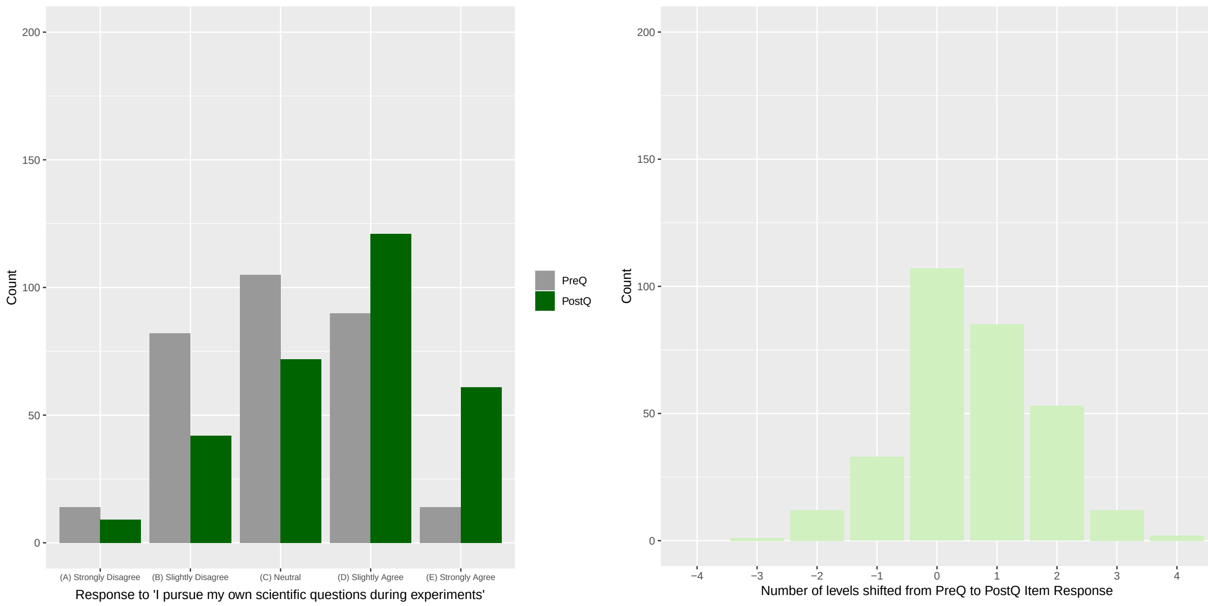


Figure B.12: **Asking Own Questions** Likert Item Pre/PostQ responses, **5AL 18W**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.57 Likert Levels was shown to be statistically significant. Additional statistics shown in Table B.19

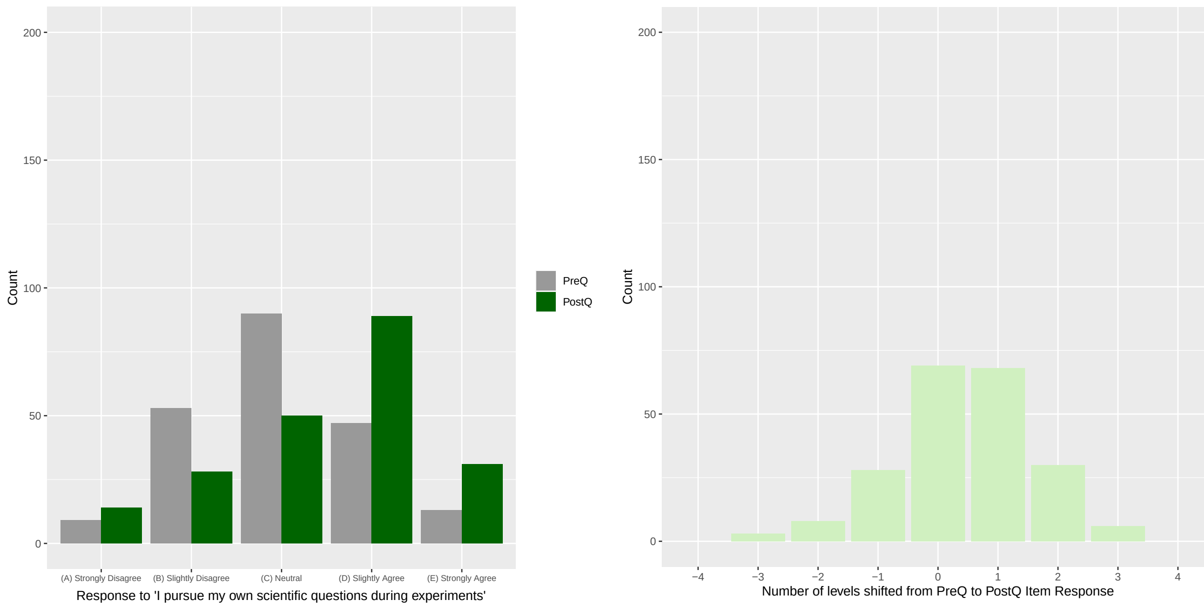


Figure B.13: **Asking Own Questions** Likert Item Pre/PostQ responses, **5AL 18S**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.44 Likert Levels was shown to be statistically significant. Additional statistics shown in Table B.20

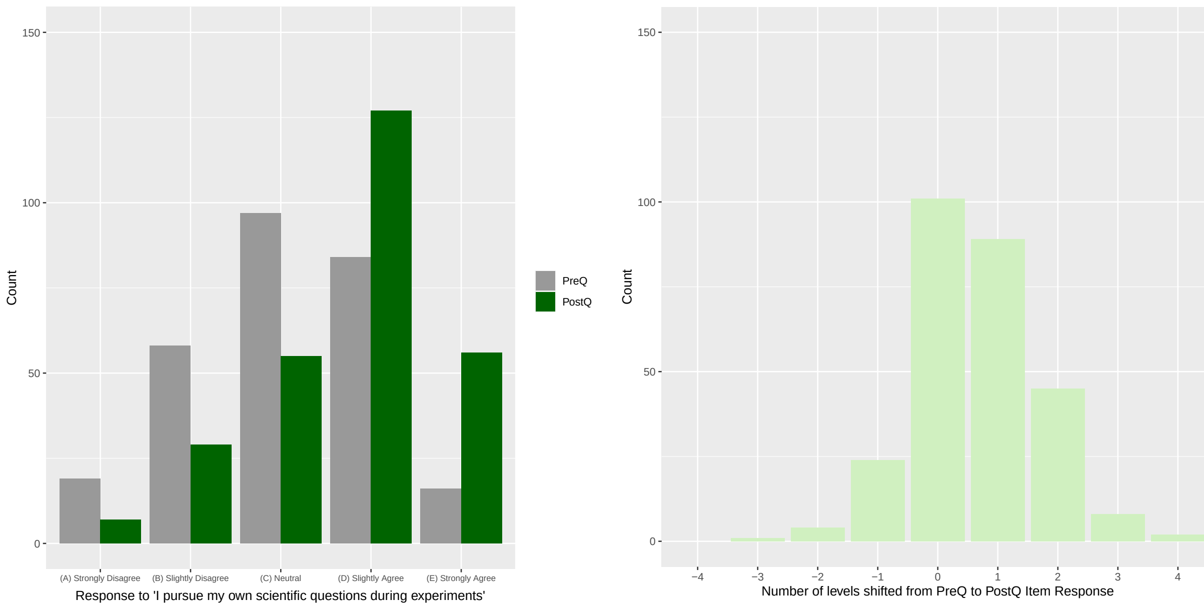


Figure B.14: **Asking Own Questions** Likert Item Pre/PostQ responses, **5AL 19W**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.64 Likert Levels was shown to be statistically significant. Additional statistics shown in Table B.22.

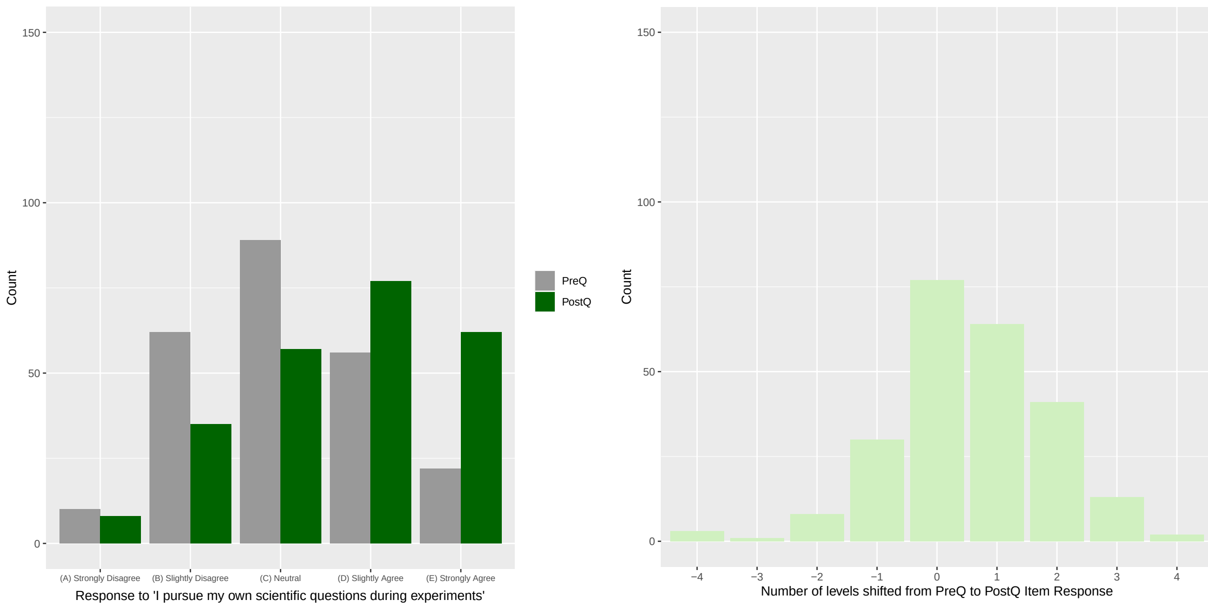


Figure B.15: **Asking Own Questions** Likert Item Pre/PostQ responses, **5AL 19S**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I usually think up my own questions to investigate.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of 0.55 Likert Levels was shown to be statistically significant. Additional statistics shown in Table B.23.

B.4.3 Ask Instructor

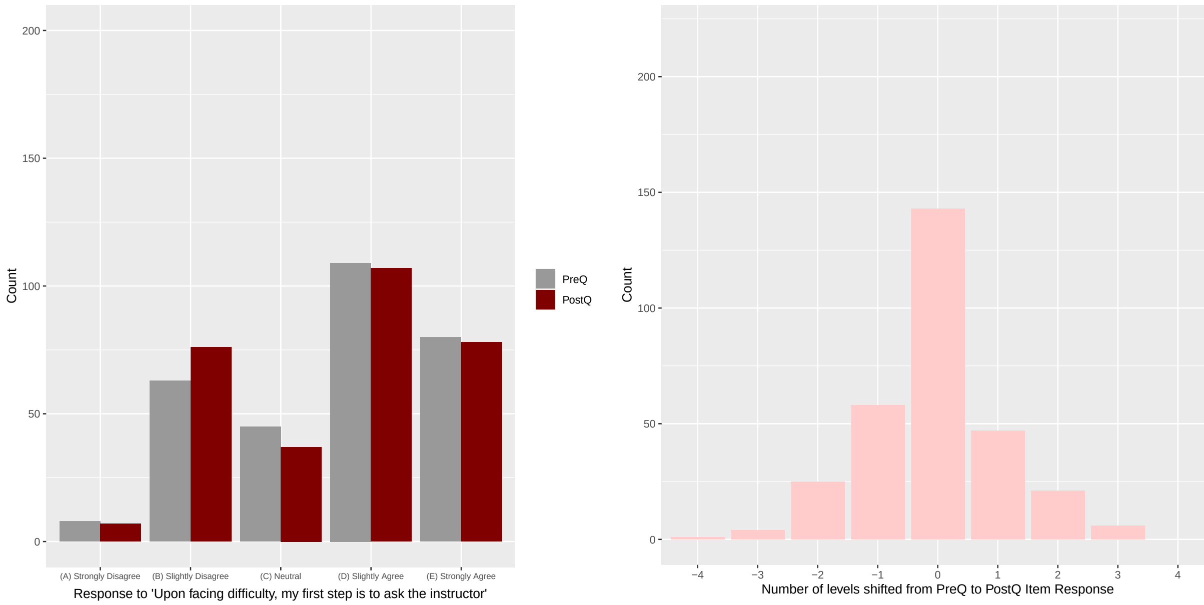


Figure B.16: **Ask Instructor** Likert Item Pre/PostQ responses, **5AL 18W**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.056 Likert Levels was not statistically significant. N = 305. Additional statistics shown in Table B.19.

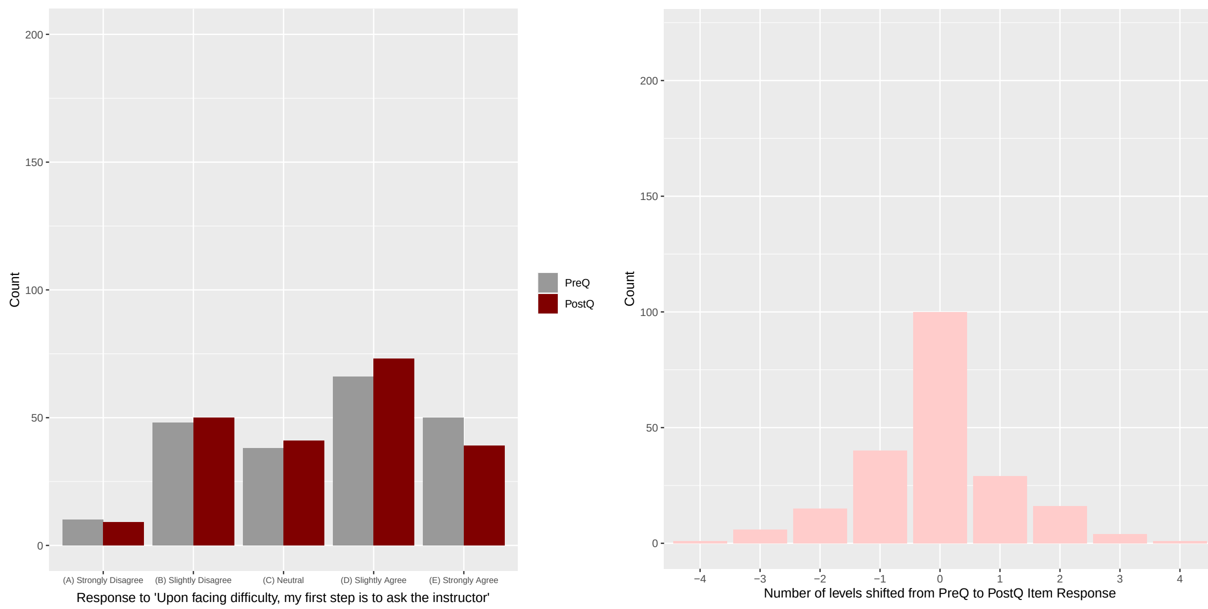
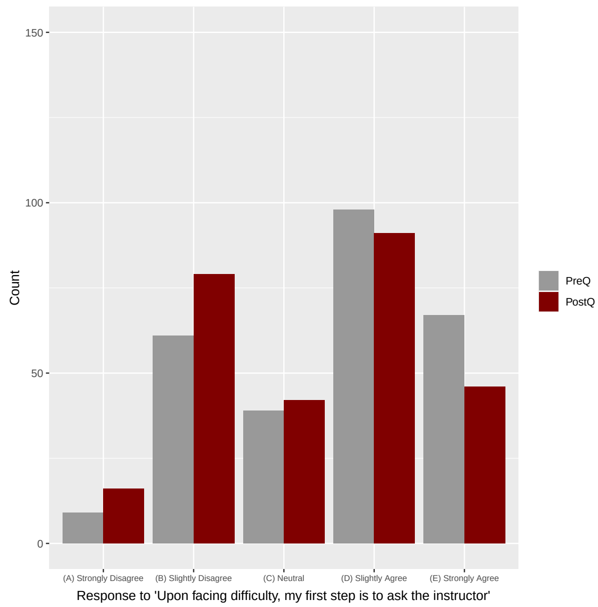


Figure B.17: **Ask Instructor** Likert Item Pre/PostQ responses, **5AL 18S**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.071 Likert Levels was not statistically significant. N = 212. Additional statistics shown in Table B.20.



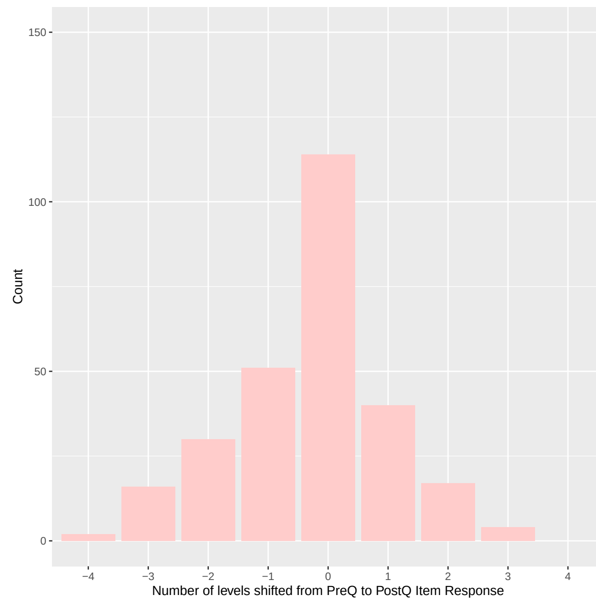


Figure B.18: **Ask Instructor** Likert Item Pre/PostQ responses, **5AL 19W**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.30 Likert Levels was statistically significant. N = 274. Additional statistics shown in Table B.22.

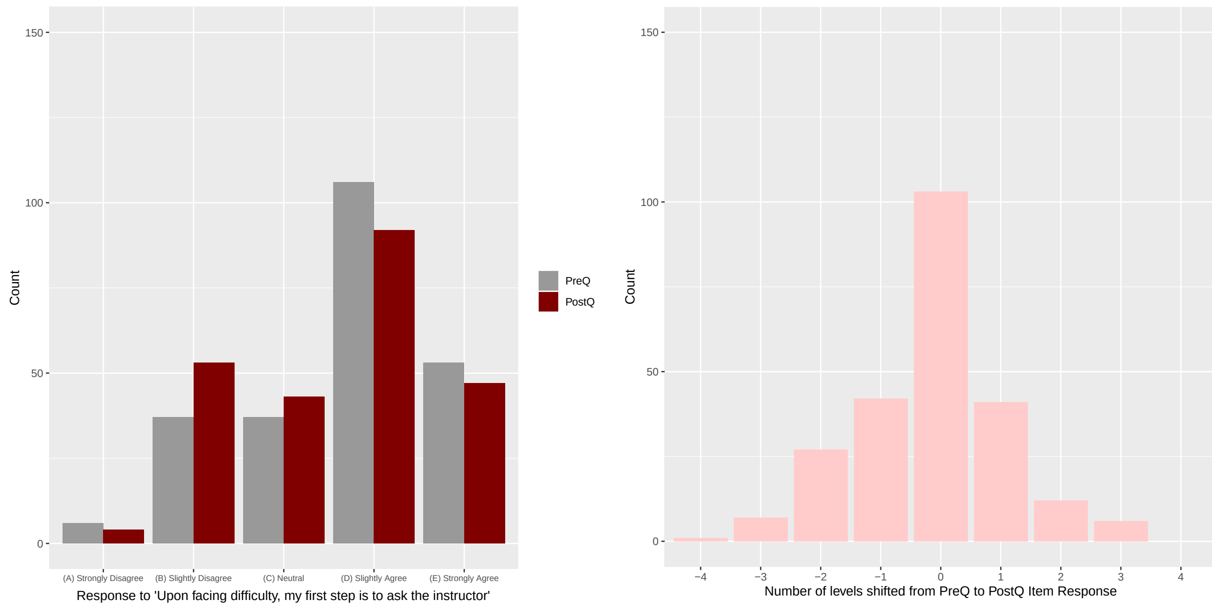


Figure B.19: **Ask Instructor** Likert Item Pre/PostQ responses, **5AL 19S**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.16 Likert Levels was not statistically significant. N = 239. Additional statistics shown in Table B.23.

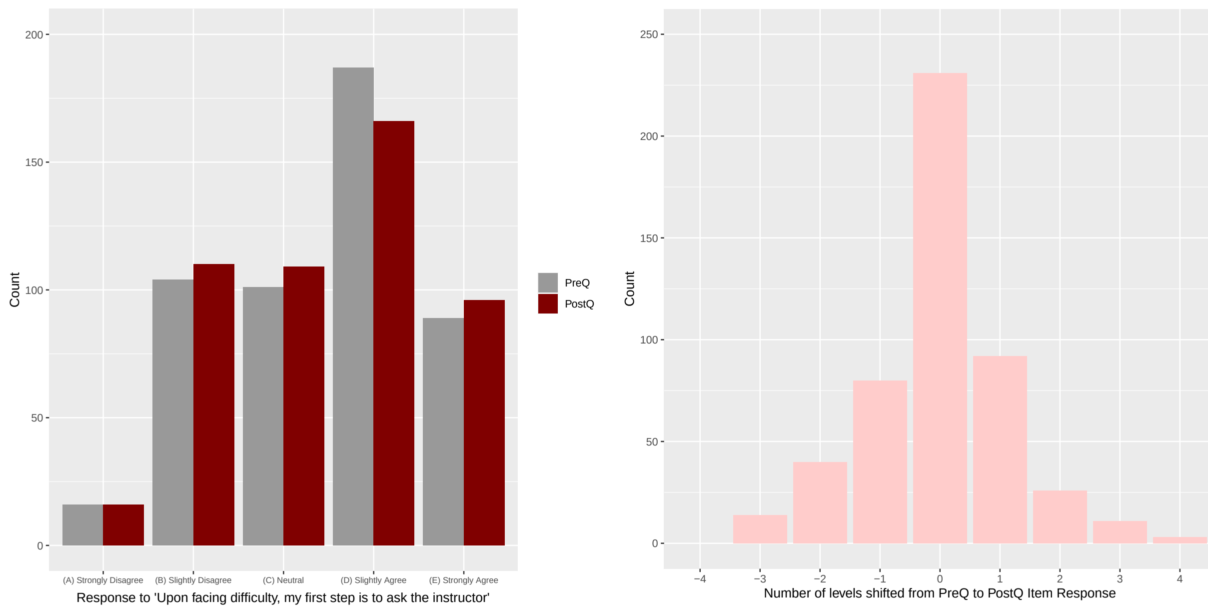


Figure B.20: **Ask Instructor** Likert Item Pre/PostQ responses, **5BL 18W**. Student feedback regarding how much they identified with the statement, *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of -.056 Likert Levels was not statistically significant. N = 497. Additional statistics shown in Table B.24.

B.4.4 Follow Instructions

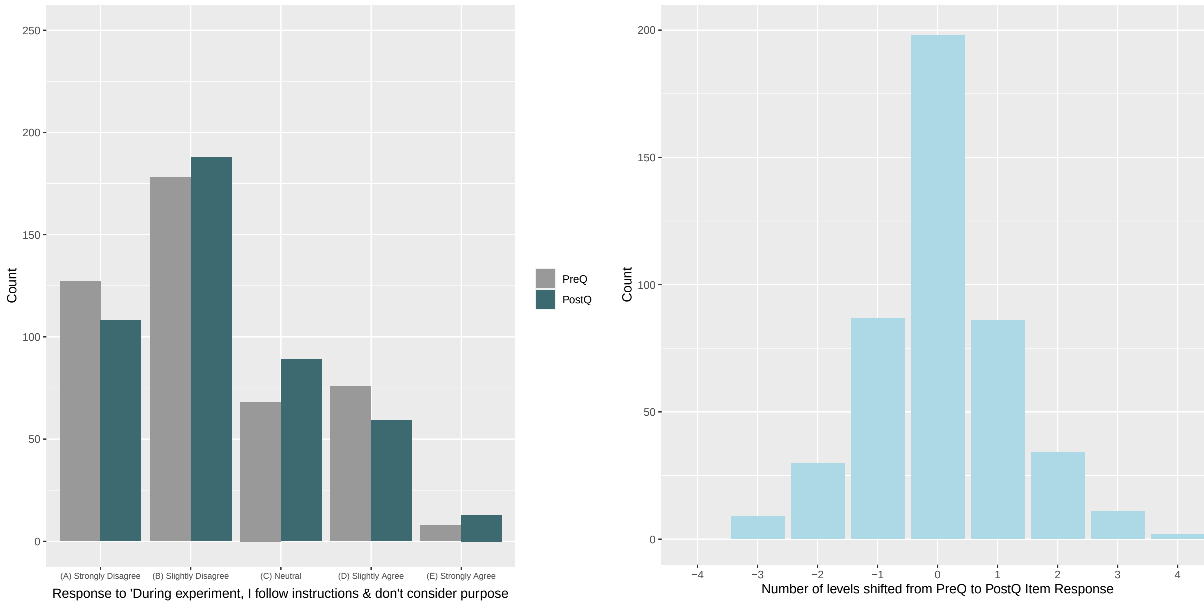


Figure B.21: **Follow Instructions** Likert Item Pre/PostQ responses, **5AL 17F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .043 Likert Levels was not statistically significant. N = 350. Additional statistics shown in Table B.18.

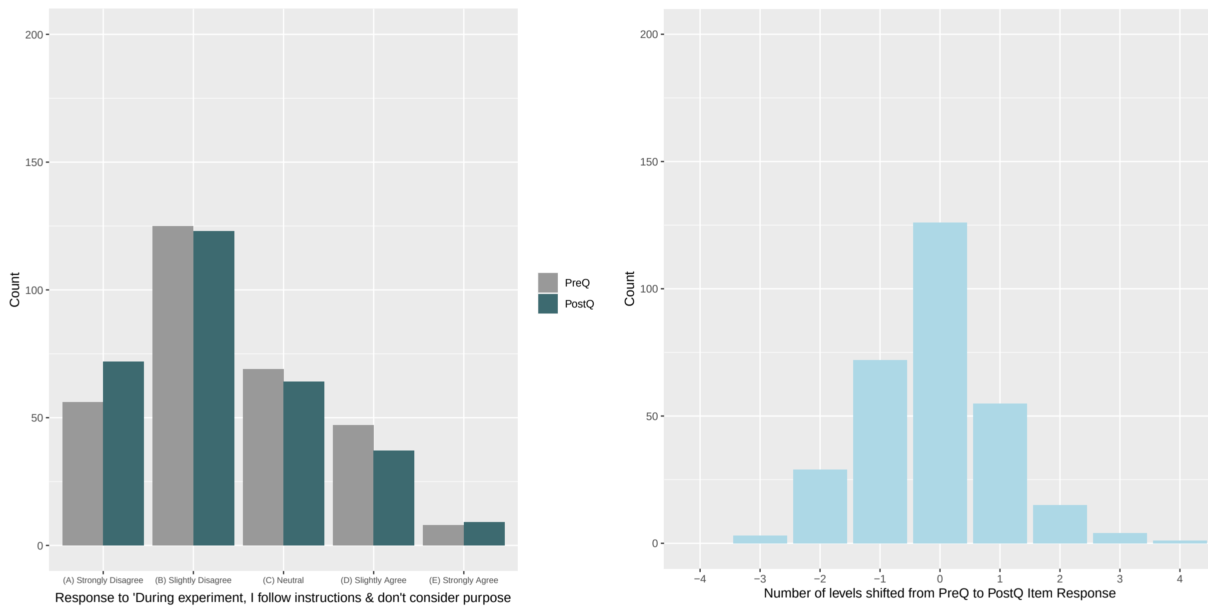


Figure B.22: **Follow Instructions** Likert Item Pre/PostQ responses, **5AL 18W**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .13 Likert Levels was statistically significant. N = 305. Additional statistics shown in Table B.19.

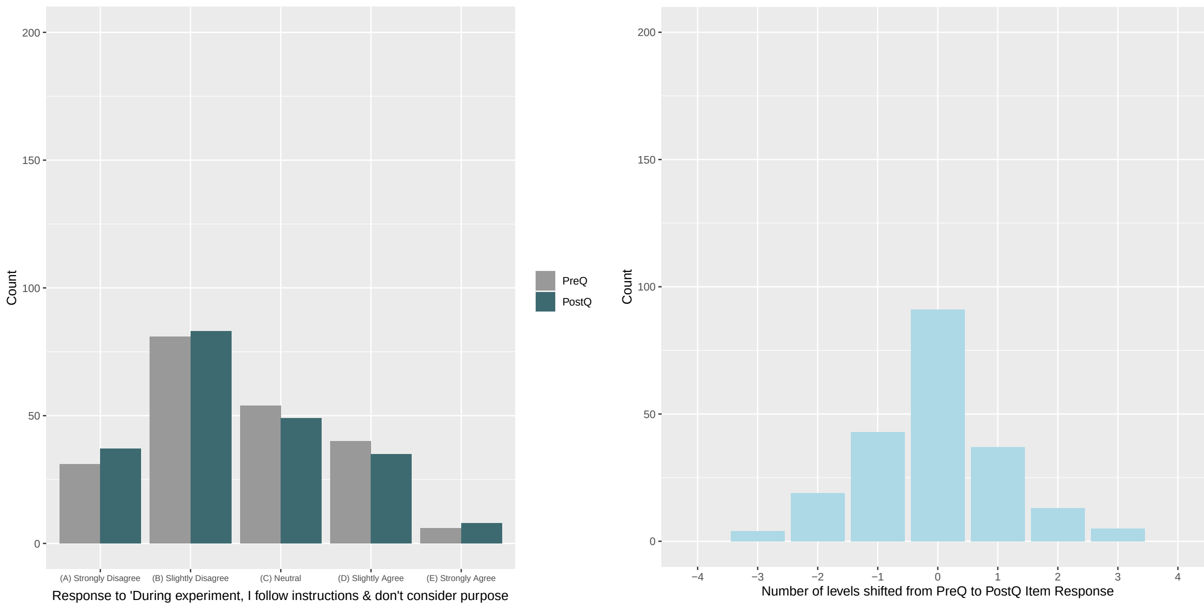


Figure B.23: **Follow Instructions** Likert Item Pre/PostQ responses, **5AL 18S**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .071 Likert Levels was not statistically significant. N = 212. Additional statistics shown in Table B.20.

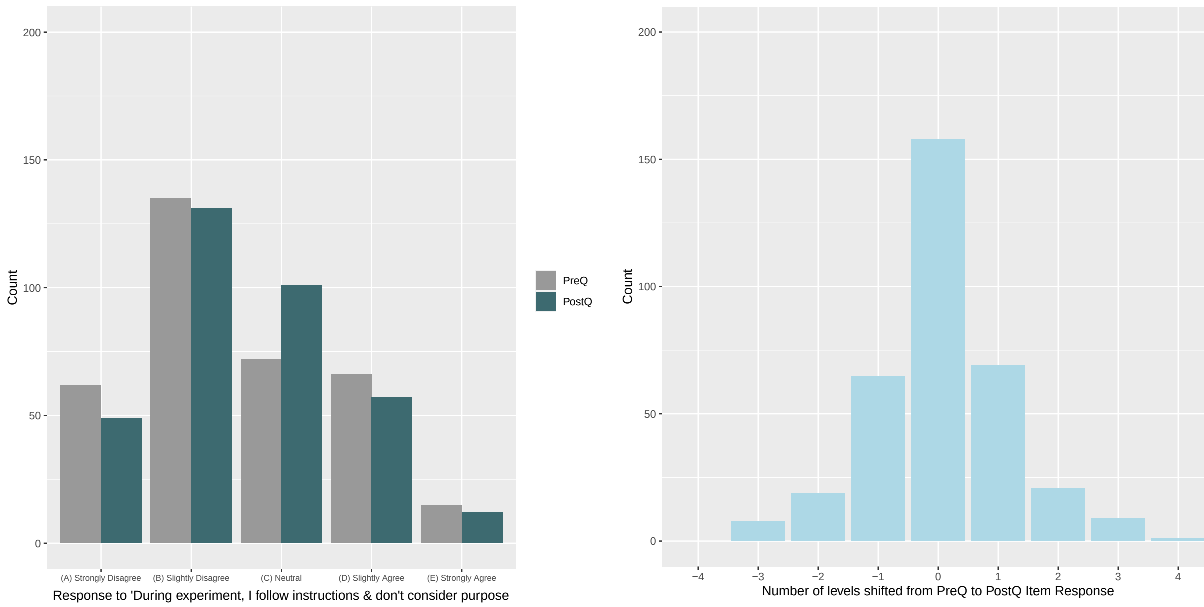


Figure B.24: **Follow Instructions** Likert Item Pre/PostQ responses, **5AL 18F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .043 Likert Levels was not statistically significant. N = 350. Additional statistics shown in Table B.21.

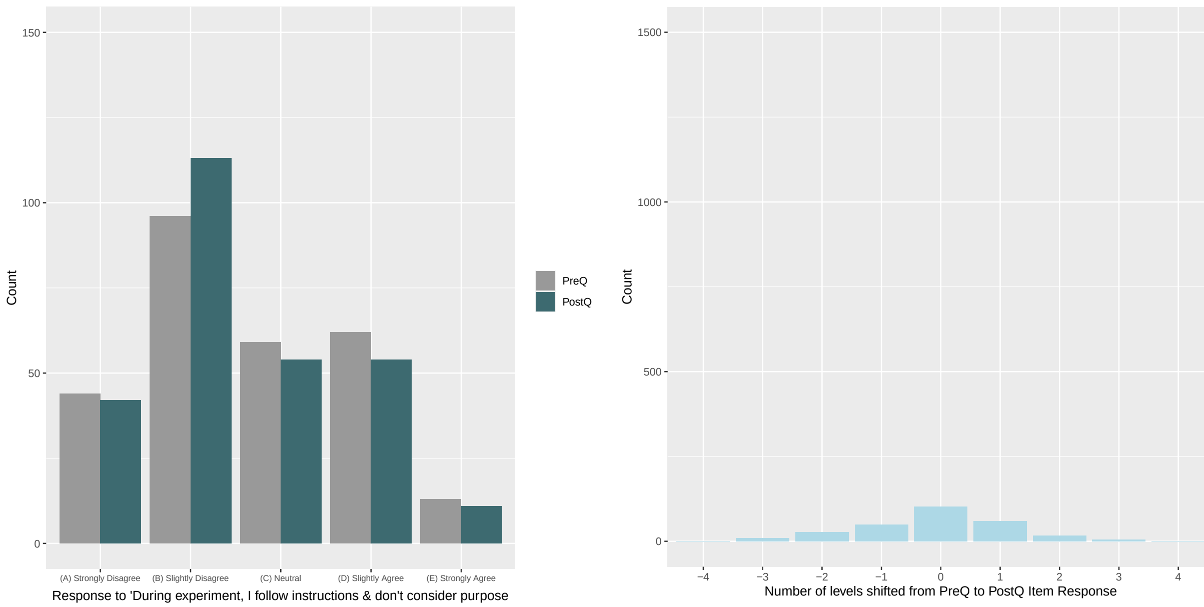


Figure B.25: **Follow Instructions** Likert Item Pre/PostQ responses, **5AL 19W**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .091 Likert Levels was not statistically significant. N = 274. Additional statistics shown in Table B.22.

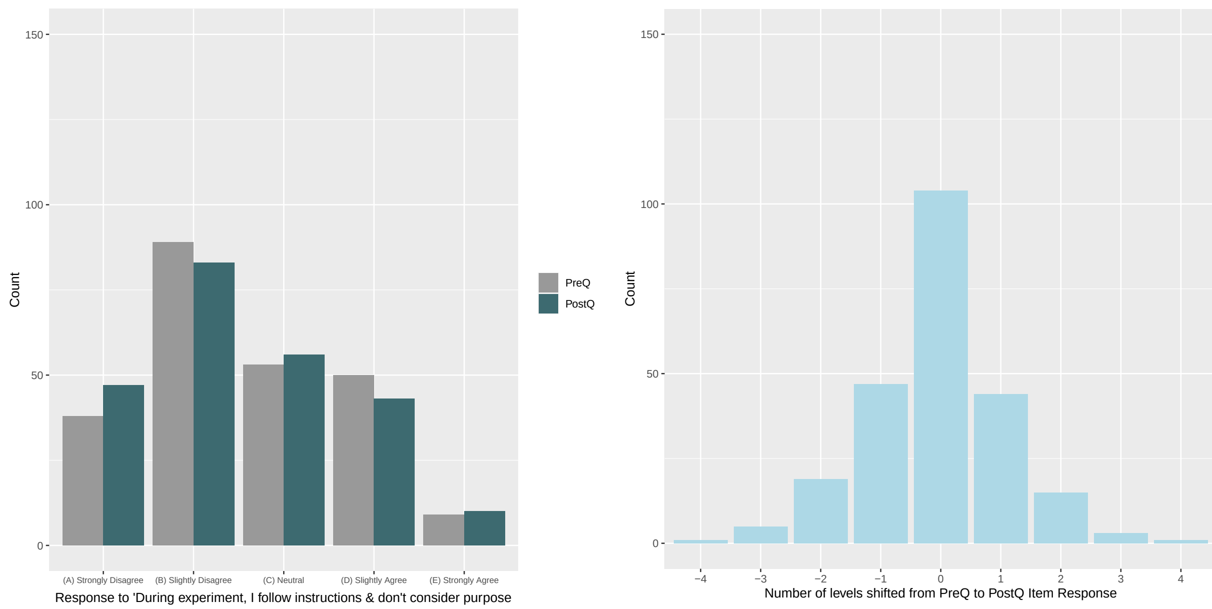
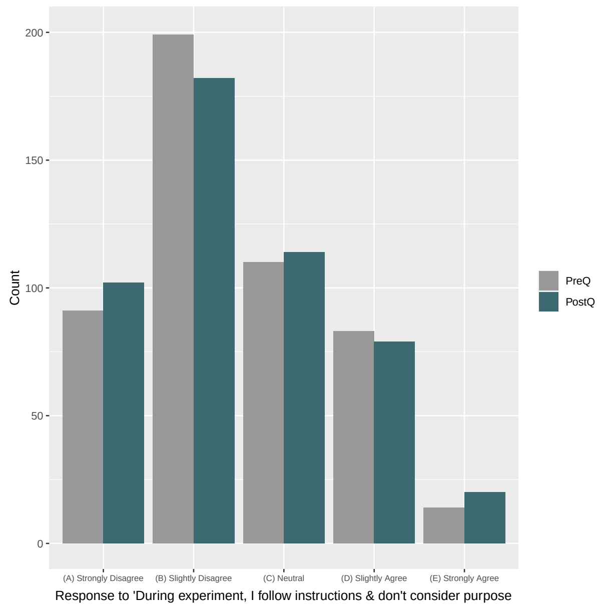


Figure B.26: **Follow Instructions** Likert Item Pre/PostQ responses, **5AL 19S**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .006 Likert Levels was not statistically significant. N = 239. Additional statistics shown in Table B.23.



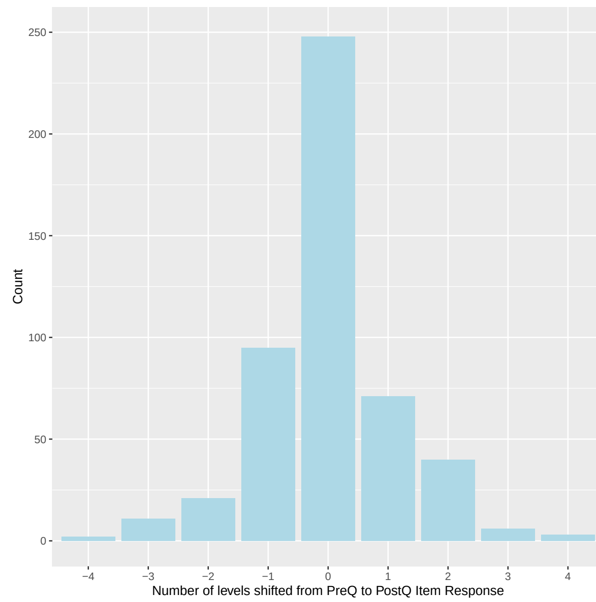


Figure B.27: **Follow Instructions** Likert Item Pre/PostQ responses, **5BL 18W**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.* **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .006 Likert Levels was not statistically significant. N = 497. Additional statistics shown in Table B.24.

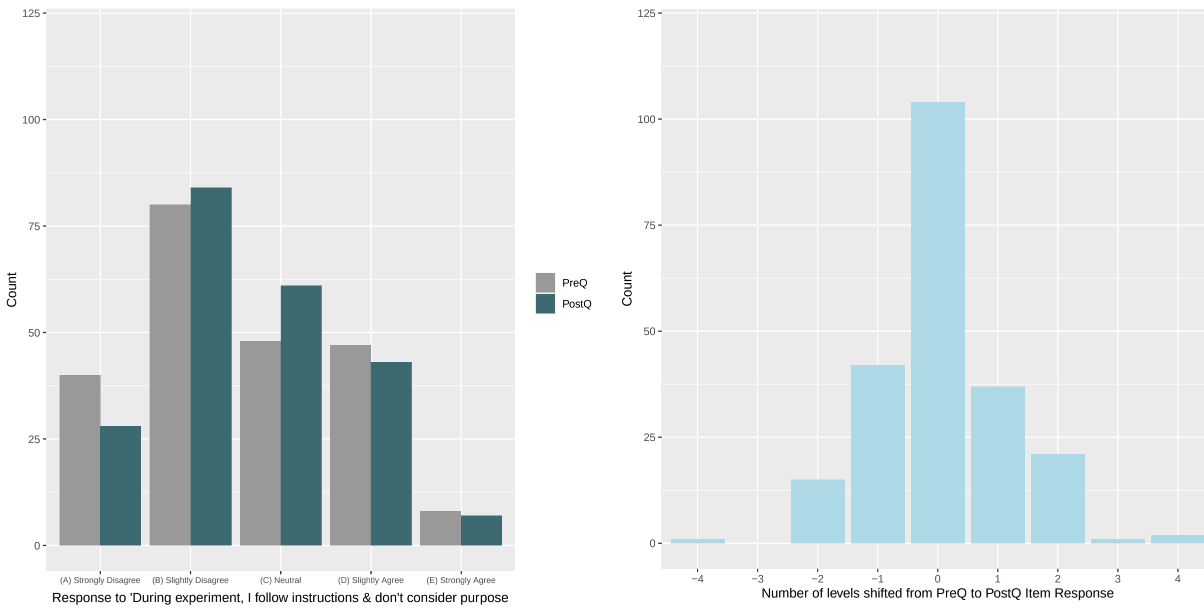


Figure B.28: **Follow Instructions** Likert Item Pre/PostQ responses, **6BL 17F**. Student feedback regarding how much they identified with the statement, *When doing an experiment, I just follow the instructions without thinking about their purpose.*. **Left.** Pre and post quarter responses, for all students who had pre/post quarter paired data. **Right.** Pre-Post quarter attitude shifts, for all students who answered both pre quarter and post quarter surveys. An average shift of .063 Likert Levels was not statistically significant. N = 223. Additional statistics shown in Table B.25.

B.4.5 RGY Card Usage affects student attitudes!

Lastly, we discuss here some details about the Red, Green Yellow (RGY) Card system implemented into the IPLS mechanics laboratory before the second year of revisions. In order to incentivize and support students to internally reflect and converse as a group upon laboratory challenges, we enforced a policy whereby students needed to "struggle" autonomously for at least two minutes before asking the instructor for help. Such timing mechanism was orchestrated by a card system, at the desk of every lab group, which could be either Green, Yellow or Red, and represented the current status of the group. At the start of every lab, the card was green, but when any member of a lab group wanted to ask an instructor for help, the entire group needed to agree to turn their card from green to yellow, and to keep their card there for two minutes before turning it to red. When the card was Red, then the TA or LA (instructor) would come over and support the lab group. Student were encouraged to read their lab manual, discuss with their group, review their pre-lab, or even consult students in other lab groups, during their two-minute "intermediate" time.

In practice, this intervention was not easily implemented, especially since the laboratory sections were run by a variety of TAs, who had varying level of expertise in implementing such pedagogy and structure into the classroom environment. Usage of the Red, Green, Yellow Card system was measured through classroom observations, using a modified COPUS mechanism, whereby buttons to track the instructor's behavior were modified to measure the level of student RGY card usage through each 2-minute interval of the class Smith et al. (2013). From these observations, laboratory sections, as categorized by TA, were grouped into "Never" used intervention, "Rarely" used intervention, and "Often" used intervention. Some laboratory sections were not able to be observed and were thus grouped into a category called "Not observed." Because each TA was only observed once, all laboratory sections to that TA were grouped into the same intervention-use category as determined by that single observation.

When attitude shift test-statistics are computed, based on each intervention-use level group, we find statistically significant, and counter-intuitive results. Figure B.26 shows comprehensive statistics are shown for the means and medians of the pre quarter, post quarter and during quarter shift student attitudes, for the attitude statement, “When I encounter difficulties in the lab, my first step is to ask the instructor for help,” referred to as the shorthand of “Ask instructor.” Interesting, the laboratory sections with the TAs whose students were observed to “often” implement the RGY card system showed the least level of attitude shift. While all sections did show nonzero attitude shifts such that students were identifying less with the statement that they needed to ask the instructor help, the group that “Often” used the cards was not statistically significant and showed the least shift. Additionally, the group that was observed to “never” turn their cards to yellow was observed to show the largest attitude shift, that was very much statistically significant. The laboratory sections that “Rarely” used the card system had an intermediate level of attitude shift, with an intermediate level of statistical significance.

Figure B.27 shows comprehensive statistics are shown for the means and medians of the pre quarter, post quarter and during quarter shift student attitudes, for the attitude statement, “When doing an experiment, I usually think up my own questions to investigate,” referred to as the shorthand of “Own Questions.” Interestingly the laboratory group that was observed to “Often” use the intervention showed the lowest attitude shifts in this category, meaning that students were not identifying as much with the statement that they were making their own scientific questions. Such results suggest that the explicit structure of using this card system may have been too rigid for the students, and the classrooms that were observed to successfully use the structure may have been doing so at the cost of creativity and benefit to the students.

Categorization of how frequently a lab section used the RGY card system was based on a single laboratory observation, where the frequency of switching a green card to a yellow card was observed and recorded. This is not a perfect measurement of how much students were using the system, because it only counted the times that a student used it when they needed help, not accounting for the fact that students might not have questions, but could still be using the system, if and when they needed help. Additionally, there is a confounding

Test Statistic	Observed Red/Green/Yellow Card usage			
	Never	Rarely	Often	Not Observed
PreQ Median	4	4	4	4
PostQ Median	3	4	3	4
QShift Median	0	0	0	0
PreQ Mean	3.62	3.82	3.31	3.45
PostQ Mean	3.24	3.57	3.25	3.29
QShift Mean	-0.38	-0.24	-0.06	-0.16
Median QShift p-value	0.0031	0.012	0.86	0.19
Median Qshift S-count	34	46	16	29

Table B.26: **"Ask Instructor" test statistics, categorized by GRY card usage.** This table shows 5AL Student attitude metrics, associated with Likert Scale statement: *When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor*, categorized by observed Red/Yellow/Green Card Usage during laboratory section. The Likert scale ranges from 1-5, with 1 being "Strongly Disagree" and 5 being "Strongly Agree."

variable between TA and RGY card implementation. Only one section of each TA was able to be observed, and the observation at that time was extrapolated to all other sections that TA taught. Therefore, there is a strong correlation in our analysis between RGY card ranking and TA. It could be that the TAs who were able to implement the intervention such that students were observed to turn their green cards to yellow, were also enforcing more structure into the lab, or interacting with the students in such a way as to change their overall philosophy about asking their own scientific questions or requesting help from the instructor. It could be that the intervention made the TA more approachable, and so student mindset changed to think more fondly of asking the instructor for help, OR that the TAs who were able to successfully implement the intervention were, in general TAs who

Test Statistic	Observed Red/Green/Yellow Card usage			
	Never	Rarely	Often	Not Observed
PreQ Median	3	3	3	3
PostQ Median	4	4	3	4
QShift Median	0	0	0	1
PreQ Mean	3.04	3.09	3.13	2.86
PostQ Mean	3.45	3.62	3.29	3.59
QShift Mean	0.42	0.54	0.15	0.72
Median QShift p-value	0.0012	3.72e-06	0.405	3.76e-05
Median Qshift S-count	14	20	15	15

Table B.27: **"Own Questions" test statistics, categorized by GRY card usage.** 5AL Student attitude metrics, associated with Likert Scale statement: *When doing an experiment, I usually think up my own questions to investigate.*, categorized by observed Red/Yellow/Green Card Usage during laboratory section. The Likert scale ranges from 1-5, with 1 being "Strongly Disagree" and 5 being "Strongly Agree."

engaged more with their students such that, even without the RGY card intervention, their students would have responded more likely to ask for help.

However, even if it is the case that the TAs themselves, are intrinsicly responsible for the student attitude shift, this is an important observation. The fact that students can have different attitude shifts during the quarter, based on the specific practices of the TA, is useful information in considering the effort we put into TA training, and paying attention to how TAs are interacting with students during the laboratory sections.

Students in laboratory sections run by a TA where moderate RGY card usage was observed, actually showed the least amounts of desired shift, for either Likert attitudinal metric assessed.

Every laboratory station was set up with a red, green, and yellow care, that could be velcroed to the back of of the lab group's computer monitor, such that the. TA and LAs could take continual survey of the room and assess the state of the every group in the classroom. All laboratory sections started on green, and students were instructed to change their card when they had a question or needed help. Instead of immediately changing their card to red, students were instructed to turn their card to yellow, to signify to the TA that they were not confident in their work. Students were to challenge themselves, as group for two minutes, to try to find the answer on their own, consulting their laboratory manual, online resources, or eve talking with other students in the laboratory section. If the students were not able to answer their own question within two minutes, then they could turn their card to red, and the TA or LA (instructor) would come over. In this case, the instructor could ask them what they had tried, in their attempts to solve their problem, and there would be more critical thinking and autonomous learning involved in the students' laboratory experience.

Overall, student attitudes did shift positively during this time, so there is evidence for a correlation between the RGY card intervention and improved student attitudes around critical thinking and persistence in learning/overcoming challenges. Additional analysis is required to better understand the causal relationship of this specific pedagogical intervention.

REFERENCES

Abdollahi, R. O., Kolster, H., Glasser, M. F., Robinson, E. C., Coalson, T. S., Dierker, D., Jenkinson, M., Van Essen, D. C., and Orban, G. A. (2014). Correspondences between retinotopic areas and myelin maps in human visual cortex. *Neuroimage*, 99:509–524.

Anstis, S. M. (1974). A chart demonstrating variations in acuity with retinal position. *Vision research*, 14(7):589.

Arisaka, K. (in prep.). Holographic visual perception of space and shape by multi-band brainwaves.

Baars, B. J. and Gage, N. M. (2010). *Cognition, brain, and consciousness: Introduction to cognitive neuroscience*. Academic Press.

Beyeler, M., Nanduri, D., Weiland, J. D., Rokem, A., Boynton, G. M., and Fine, I. (2019). A model of ganglion axon pathways accounts for percepts elicited by retinal implants. *Scientific reports*, 9(1):1–16.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, 226(5241):177–178.

Bouma, H. (1971). Visual recognition of isolated lower-case letters. *Vision research*, 11(5):459–474.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial vision*, 10(4):433–436.

Chen, Y.-R., Chao, K., and Kim, M. S. (2002). Machine vision technology for agricultural applications. *Computers and electronics in Agriculture*, 36(2-3):173–191.

Chung, S. T. (2007). Learning to identify crowded letters: does it improve reading speed? *Vision research*, 47(25):3150–3159.

Crouch, C. H., Wisittanawat, P., Cai, M., and Renninger, K. A. (2018). Life science students' attitudes, interest, and performance in introductory physics for life sciences: An exploratory study. *Physical Review Physics Education Research*, 14(1):010111.

Dowling, J. (2005). Artificial human vision. *Expert Review of Medical Devices*, 2(1):73–85.

Fiebelkorn, I. C. and Kastner, S. (2019). A rhythmic theory of attention. *Trends in cognitive sciences*, 23(2):87–101.

Flom, M. C., Heath, G. G., and Takahashi, E. (1963). Contour interaction and visual resolution: Contralateral effects. *Science*, 142(3594):979–980.

He, S., Cavanagh, P., and Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature*, 383(6598):334–337.

Hebb, D. O. (1949). *The organization of behavior: a neuropsychological theory*. J. Wiley; Chapman & Hall.

Horton, J. C. and Hoyt, W. F. (1991a). Quadrantic visual field defects: a hallmark of lesions in extrastriate (v2/v3) cortex. *Brain*, 114(4):1703–1718.

Horton, J. C. and Hoyt, W. F. (1991b). The representation of the visual field in human striate cortex: a revision of the classic holmes map. *Archives of ophthalmology*, 109(6):816–824.

Intriligator, J. and Cavanagh, P. (2001a). The spatial resolution of visual attention. *Cognitive psychology*, 43(3):171–216.

Intriligator, J. and Cavanagh, P. (2001b). The spatial resolution of visual attention. *Cognitive psychology*, 43(3):171–216.

Knight, R., Jones, B., and Field, S. (2013). *University Physics for the Life Sciences*. Pearson.

Olshausen, B. A., Anderson, C. H., and Van Essen, D. C. (1993). A neurobiological model of visual attention and invariant pattern recognition based on dynamic routing of information. *Journal of Neuroscience*, 13(11):4700–4719.

Peirce, J. W. (2007). Psychopy—psychophysics software in python. *Journal of neuroscience methods*, 162(1-2):8–13.

Qi, B., Bao, Y., and Nakata, T. (2006). A log-polar transformation method for face recognition. In *SCIS & ISIS SCIS & ISIS 2006*, pages 279–284. Japan Society for Fuzzy Theory and Intelligent Informatics.

Reich, L. N. and Bedell, H. E. (2000). Relative legibility and confusions of letter acuity targets in the peripheral and central retina. *Optometry and Vision Science*, 77(5):270–275.

Smith, D. P., McNeil, L. E., Guynn, D. T., Churukian, A. D., Deardorff, D. L., and Wallace, C. S. (2018). Transforming the content, pedagogy and structure of an introductory physics course for life sciences majors. *American Journal of Physics*, 86(11):862–869.

Smith, M. K., Jones, F. H., Gilbert, S. L., and Wieman, C. E. (2013). The classroom observation protocol for undergraduate stem (copus): a new instrument to characterize university stem classroom practices. *CBE—Life Sciences Education*, 12(4):618–627.

Strasburger, H., Rentschler, I., and Jüttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of vision*, 11(5):13–13.

Whitney, D. and Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in cognitive sciences*, 15(4):160–168.

Wilcox, B. R. and Lewandowski, H. J. (2016). Students' epistemologies about experimental physics: Validating the colorado learning attitudes about science survey for experimental physics. *Physical Review Physics Education Research*, 12(1):010123.

Zhao, J., Liang, B., and Chen, Q. (2018). The key technology toward the self-driving car. *International Journal of Intelligent Unmanned Systems*.