Cognitive science is facing a hard problem(Chalmers, 1995): we have no idea how neural activity generates the rich first-person experience of consciousness. This problem is difficult not only because of our uncertainty about the solution but because we **do not know what a solution will look like**. Because of this I find the hard problem of consciousness particularly compelling—a question that requires a paradigm shift in our thinking. Pursuing an answer has driven me to develop a broad background spanning neurobiology, computer science, and cognitive neuroscience and is pushing me to build a research program that extends across these diverse fields.

**Consciousness**

It seems ironic that a phenomenon we all experience has yet to be pursued with much rigor, but cognitive neuroscience has largely sidestepped consciousness in favor of studying cognition. This has occurred for several reasons: consciousness is known to be difficult—many researchers believe it is premature to study. But more puzzling is the belief that consciousness is a philosophical issue and that there is something unknowable about consciousness. In the last 20 years this belief has been replaced by a search for neuronal processes in the brain that correlate with consciousness (Crick and Koch, 1992). The search for neural correlates of consciousness (NCC) is based on the assumption that consciousness is a thing in the brain that we need to find, like the gene was for DNA. I believe that assumption is incorrect: consciousness is a distributed neural process and likely has a unique signature for every different experience. Because of this the search for NCC will only succeed at finding neural processes that do not correlate with any kind of consciousness. Instead, I believe **consciousness needs to be understood as a computation**—the brain’s solution to a functional problem that we don’t yet fully grasp.

Early in my undergraduate career at Cornell I took a course on consciousness. Prof. Shimon Edelman’s goal in the class was to impose on us the importance of thinking not only about *what* a cognitive phenomenon is and *where* the brain represents it, but also *why* the brain should bother with it and *how* the brain computes it. This is exactly the kind of paradigm shift in thinking that has occurred for other cognitive processes, such as attention. Attention in the psychology literature used to be invoked as a spotlight that swept through sensory space and highlighted important events. Research in cognitive neuroscience now suggests that although the function of attention overlaps across sensory domains its implementation is unique in each space. In vision, for example, attention acts as a form of sensory enhancement, introducing a gain change on the response to visual inputs. It makes sense to think that in the abstract consciousness may share similarities to attention: consciousness is a computational solution that is shared across brain areas to solve a variety of functional problems.

To understand consciousness as a function requires asking why a brain might need to be conscious and what kinds of computations are necessary to solve those functions. Traditional philosophers have also thought about this issue—and have been stumped by apparent paradoxes. Take the philosophical zombie (or its modern incarnation: the conscious computer), the p-zombie is a perfect copy of a human that simply lacks conscious awareness (Stanford Encyclopedia of Philosophy, 2009). It receives inputs like a human, acts like a human, but lacks conscious experience. While some philosophers consider p-zombies a real possibility the *why* question suggests that **philosophical zombies cannot exist**. If consciousness has a function, a fitness benefit conferred to our predecessor organisms and selected for over evolutionary time, then philosophical zombies are not possible: a p-zombie with no consciousness would lack some essential function. It seems clear to me that we have yet to fully grasp the functional importance of consciousness, and that there may be significant value in searching for and understanding the functional purpose of consciousness.

I believe that to understand consciousness is to understand three questions: what benefit consciousness confers to an organism, what neurons are responsible for computing that function, and how the brain instantiates those computations in neural systems. Answering those questions does not constitute a research project but rather a research program spanning decades. My research as a graduate student pursues a small piece of this program by looking at how attention acts as a gateway to consciousness. When we attend to something we become immediately aware of it: what function does bringing something into consciousness provide for an organism and what neural systems are responsible for its implementation?

**Background and Past Research**

Before pursuing graduate work I took time off to improve my skills as a cognitive neuroscientist and to learn about and live in a new culture. I found an ideal climate to pursue these goals in Prof. John-Dylan Haynes’ research group in Berlin, Germany. Prof. Haynes gave me the opportunity to work on an exciting and challenging research question looking at whether our intuitions about decision making are reflected in neural processing. When we make a decision we have a conscious experience that the decision occurs at a precise moment. But this intuition does not match the neural activity in our brain: Prof. Haynes had shown in a previous experiment that early brain activity could be used to predict an action 8 seconds in advance of the experienced moment of decision making (Soon et al., 2008). We wanted to further study this process to understand how late a person might still be able to “veto” their decision in real time. To understand this question we devised a predictive brain computer interface which monitored a subject’s EEG patterns in real time. The computer then fed back a signal whenever it predicted an upcoming movement decision. We found that up until 200 ms before movement onset participants would see the signal and then entirely cancel their action, showing no overt sign of a decision. This suggests that this earlier EEG activity we pick up is predictive of the decision, but not responsible for it. In the last 200 ms before movement onset though it became impossible for participants to cancel the beginning of their movement, although they were able to stop the movement prior to completion. Comparing our results with a computational model (Schurger et al., 2012) we found strong similarities, confirming that our result may indeed be the last “point of no-return” within the brain before efferent neural activity is sent to the muscles. At the time of this submission our manuscript is in revisions at PNAS.

The entire research process, from formulating our research question, finding appropriate technological resources to create a brain-computer interface, analyzing data, and finally creating a publishable paper, has been an enjoyable and immensely rewarding experience. Working with Prof. Haynes cemented my goal of becoming a professor and reinforced my belief that academia is the right place to be pursuing consciousness research at this time.

**Stanford University**

My broad background from Cornell spanning neurobiology and computer science, combined with my work with Prof. Haynes helped me obtain admission to Stanford where I am now developing my research program. With my adviser, Prof. Justin Gardner, I have begun a project investigating the neural process of attention and how it acts as a gateway to consciousness. I am building on the platform of Prof. Gardner’s previous work, which showed that spatial attention introduces a selection bias in the brain’s early visual representations (Pestilli et al., 2011). My own work is focused on developing a model that explains the impact of feature-based attention on visual perception. My NSF research proposal is a continuation of this research project, looking into the predictions that our model makes through a different research tool: transcranial magnetic stimulation. My prediction is that **attention is a neural process that acts only as a form of sensory enhancement**, but is not ultimately responsible for generating conscious experience.

Working at Stanford is not only an opportunity to collaborate with world class researchers and develop my own research program. It is also an opportunity for me to develop additional quantitative skills. Although I gained considerable research experience as an undergraduate at Cornell and during my time in Berlin, I did not acquire a deep understanding of the techniques I was using. At Cornell I learned to perform microelectrode recording and chemical lesions in the lab of Prof. Thomas Cleland. While in Berlin I gained practical experience recording both EEG and fMRI. One of my goals for my graduate career is to become an expert in human neuroscience and eventually teach these same techniques to future students. In my first year I pursued this goal by diving more deeply into understanding functional MRI. I took classes on the physics of MRI and learned about sequence development. Putting my theoretical knowledge to practice I helped develop and test more advanced ‘multiplexed’ fMRI sequences that allow faster acquisitions without a loss in signal quality. These changes mean that our lab can now collect four to six times as much data, at the same voxel resolution, compared to what was considered standard in fMRI five to ten years ago. In my second year and beyond I plan to continue acquiring a detailed understanding of other neuroscience techniques. My current list includes learning about convolutional neural networks as well as gaining knowledge about transcranial stimulation systems for their use as tests of causal neural relationships in the human brain.

**Future Goals**

My goal is to become a professor of cognitive neuroscience with a focus on understanding the neural mechanisms of consciousness. Given the nature of the hard problem it is clear that this research goal will stretches across decades. The length of this goal highlights the importance of mentoring and encouraging students to pursue similar research. With this in mind my second goal during my graduate career is to improve my abilities as a teacher. This year in the fall I am a TA for the introductory graduate statistics class, and in the winter and spring I will TA for two introductory cognitive neuroscience courses. One course is aimed at undergraduates and the other at graduate students in the neuroscience department. In all of these classes and in my future teaching I hope to impart to students the necessity of looking at problems from a broad perspective. Research in cognition is increasingly multidisciplinary, drawing on psychology, biology, and computer science. Despite this, the majority of incoming graduate students still have little to no training in neurobiology and programming. My experience with consciousness research has imparted on me a strong belief that **to crack the puzzle we need to be thinking simultaneously at multiple levels of analysis**, and that students need unique tools at each level. How to push students to think in a multifaceted way is an altogether different puzzle for me and I am looking forward to broadening my views with TA opportunities and eventually teaching my own classes.

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**Studying the Neural Substrate of Attention and Visual Awareness**

Consciousness appears to be a bi-stable phenomenon: you are either aware of something, or you aren’t. In addition we have an undeniable feeling that attending to something brings it immediately to awareness. Attention appears to act as a gateway to consciousness and I believe that studying attention is a way to probe the specific mechanisms that translate visual inputs into conscious awareness. To clarify these mechanisms I am building a model of feature-based attention as a part of my research program with Prof. Justin Gardner at Stanford University. Our goal is to build a model of the neural process of feature-based attention that accounts for the evident changes that attention causes for conscious visual perception.

**Inattentional Blindness**

In the early 1990s Arien Mack and Irvin Rock discovered that attention to one feature in an image was sufficient to abolish conscious awareness of other features. They coined this phenomenon “inattentional blindness” noting that it even occurred when participants were specifically fixating (i.e. their eyes were directly centered on) the feature of which they had no perception. However, it was later shown that some features survive inattentional blindness, in particular natural images and faces (Li et al., 2002; Reddy et al., 2004). This finding led researchers like Christof Koch to announce that attention and conscious awareness were two separable processes in the brain (Koch and Tsuchiya, 2007). More recent research has re-opened the debate by suggesting that even scene perception is subject to inattentional blindness when attention is engaged by a sufficiently difficult task (Cohen et al., 2007). I propose that this mixture of results is largely due to an imprecise understanding of attention. **Attention is a specific neural process**. If we knew precisely how attention acts on other neural processes in visual cortex we would have a better grasp on understanding why attention manipulates our conscious awareness.

**Current and Proposed Studies**

Over the past year I have collected data to begin building a model of the effect of feature-based attention on neural processing in the visual cortex. Using an inattentional blindness paradigm I combined two well understood image features: image contrast and motion coherence. We know that the BOLD fMRI signal in early visual cortical areas such as V1 is sensitive to contrast intensity, but not to motion coherence. The reverse is true in the later cortical areas V3a and hMT, where there is response sensitivity to motion coherence but not to contrast intensity. Importantly, visual cortex is organized in a hierarchy where V1 projects more strongly to V3a and hMT than the converse. Based on this knowledge I expected that due to the feed-forward connections in visual cortex attentional effects would be fed to downstream cortical regions, potentially corrupting the downstream representations. Specifically, I expected that attention to contrast, which is known to affect V1, would corrupt or suppress signals in the downstream areas V3a and hMT. In contrast, I expected that attention to motion, which we expected to affect V3a/hMT, would not result in any change in the signals in V1. If discrimination of contrast depended only on V1 and motion only on V3a/hMT, then the behavioral results are clear: attention to motion should affect the perception of contrast but not vice versa. This is precisely the effect that we observed. Our BOLD fMRI results show that the responses in area hMT and V3a are modulated by the type of attention, whereas responses in V1 are not. In parallel we found that discrimination of motion in our task was affected by attention, whereas discrimination of contrast was not.

The model is currently incomplete—although we know from our data that the perception of contrast and motion are asymmetrically related to attention and that BOLD fMRI responses reflect and possibly drive perception, we still have not specified the causal process of attention. My hypothesis is that **attention to contrast corrupts the representation of motion** in the downstream regions. I will test this hypothesis in two ways: First by using a computational model of our current dataset to look at what effect of attention best explains our data, and second in a new experiment using transcranial magnetic stimulation. TMS is a technique that can be used to either abolish neural activity in a region, akin to a temporary lesion, or to boost or suppress activations that are near perceptual threshold. We can take advantage of both of these techniques to test our hypothesis in the following ways: **(1)** as a test of causality, using temporary TMS lesions to test the involvement of each area in contrast and motion perception, and (**2)** by using low-threshold pulses to mimic corrupting attentional signals. If corruption is indeed the cause of our effect than a low-threshold pulse to V1 should introduce similar corruption in downstream regions, mimicking the behavioral effects I have already observed. In this way TMS is a similar tool to the lesion experiments performed in the monkey physiology literature in the 90s. It allows us to test for causal outcomes by both temporarily abolishing activity in a region and inducing increased activation via low-threshold pulses. This is the ideal technique for testing my corruption model and the data we collect will give us considerable leverage in understanding the precise nature of feature-based attention and its impact on the perception of contrast and motion.

**Impact**

This research has the potential to help clarify the debate surrounding attention and inattentional blindness, and ultimately to improve our understanding of the neural processes of consciousness. As I build my model of feature-based attention I continue to think about how this model fits into the larger space of consciousness research. Attention is clearly an integral part of our own conscious experiences, but it remains entirely unclear whether the neural process of attention interacts directly with the neural processes of consciousness. My prediction is that attention is responsible for the bi-stability of consciousness. As a gating function and a form of sensory enhancement attention appears to influence the depth to which perceptual information is processed by the brain. It is likely that only processing that reaches a certain neural system leads to consciousness, but that model is for the moment untestable.

Understanding attention is an indirect solution, as it doesn’t directly address the question of how conscious is evoked by neural processes. I believe that question needs to be held to the side while we clarify attention, memory, and decision making—processes that are often associated with consciousness but with only a vague understanding of their associated neural processes. As these become more clear we will be able to build experiments that more precisely isolate conscious neural processes in the human brain.

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