Journal of Undergraduate Research

jur

University of Rochester

Volume Four
Issue One
Fall 2005

The *Journal of Undergraduate Research* (*jur*) is dedicated to providing the student body with intellectual perspectives from various academic disciplines. *jur* serves as a forum for the presentation of original research, thereby encouraging the pursuit of significant scholarly endeavors.

Acknowledgements

Faculty Advisor
Priscilla Auchincloss, Ph.D.

The College
William Scott Green, Dean

Professorial Review Board
Paul Ampadu, Ph.D.
Eric Blackman, Ph.D.
Chris Brown, Ph.D.
Edward Deci, Ph.D.
Andrew Elliot, Ph.D.
Daeyeol Lee, Ph.D.

From the Editors

Our undergraduate years are a time for looking forward. Some of us look forward to our upcoming careers. Some of us look forward to graduate, others to medical or law school. While each of us has a different path before us, it is our time in college that prepares us for what we must face in the world. Ultimately, our undergraduate experiences create the framework in which we will learn for the rest of our lives. As we disperse from our schools to all corners of the globe, each one of us will embark upon new and different learning experiences. How we come to understand our jobs, continuing education, and responsibilities in general will be shaped by these learning frameworks we create during our time as undergraduates.

Such frameworks are hardly a new concept. It is a common maxim that one "learns how to learn" while in college, and we at jur believe this wholeheartedly. As much as college is about the gathering of actual knowledge that will be useful in the future, it is also about building methodologies for understanding the world around us. And there is no better process for honing our skills of rational analysis and critical thought than research. Regardless of discipline, real research – which is readily accessible to anyone willing to look – places demands on the mind and person that shape us into more responsible, farsighted, and wiser people. We will carry these skills with us throughout college and into the world, and will depend on them to navigate through hardship, success, and everyday life.

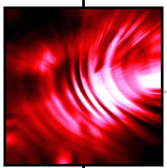
We at jur continue our commitment to excellence in undergraduate research with this new issue, which will be distributed in print across the United States, and available electronically worldwide. And that circulation reflects a firm belief that we hold: the research appearing in the pages that follow need not be qualified as 'undergraduate,' as though it is inherently less than any research appearing in traditional journals. Being necessarily enmeshed in a process of significant evolution and self-discovery does not preclude undergraduates from producing rigorously researched work. In fact, it has the potential to produce new and insightful perspectives on issues never before considered publicly. It is in that spirit that we invite you to read on, and learn a little more about how our world works.

Sincerely,

Suzanne Golisz, 2005 Jason Moore, 2005
Editors-in-Chief

University of Rochester | Volume 4 | Issue 1 | Fall 2005

jur

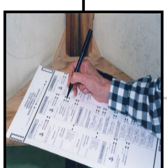


Shear Viscosity under Shock-Loading Conditions — 8
Zhuohan Liang

Featured Researcher: Fault Tolerant Behavior-Based Robots — 13
Laura Wong

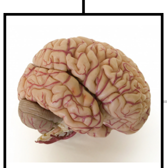
Continuous Identity Verification through Keyboard Biometrics — 20
Peter Ordal, David Ganzhorn, David Lu, Warren Fong, Jonathan Blair Norwood

Violin Acoustic Radiation Synthesis — 25
Jacob Waxman



Strength of Political Views in Young People and their Parents — 29
Laura Maruskin

Accretion Region Variability Mechanisms in Low Luminosity AGN — 33
Grant Tremblay



Ball Catching and the Role of Prediction — 38
Keith Gorgos

From the Editors, Staff - 2 | Interview - 4
Undergraduate Research Programs - 48 | Picture References - 50

Perspectives on Research

jur interviews Thomas Smith, Ph.D.

Thomas Smith is Professor of Sociology at the University of Rochester.

jur: What kind of research are you involved with?

Smith: I've always been interested in strong personal ties. They were taken up in the study of the so-called primary groups in my field. I had sort of drifted away from that for a while, but came back to it in the mid-1980s, and I had an insight that many of the patterns that you see in the attachment and interaction of people who have strong emotional relationships to one another resemble patterns that you find among substance abusers. So the intuition was that a model of strong interaction and strong attachment might be discovered in models of addiction.

I began exploring that intuition and began to educate myself. I studied biology as an undergraduate at Johns Hopkins, so it wasn't entirely alien to come back to the field; I ended up writing a book around 1991 called Strong Interaction in which the argument was expanded, and it proved to be a very powerful argument that covered a great deal of territory. It went all the way from studying the interaction of infants and their caregivers all the way through studying markets and complex organizations.

I thought the theory was a very powerful approach and although I had explored, to some extent, the neurological side of addictive disorders – in particular, substance abuse and building models of substance abuse – I was uncomfortable with my handling of those materials, and I began to think that I ought to really consider the neuroscience literature.

In 1991, just when this book was about to come out, I was invited by an old friend of mine, Tom Scalea, who was the head of Trauma Medicine and Emergency Medicine at Kings County Hospital in Brooklyn, to consult with him about chronic violence among adolescents. He invited me down and he said: "We're being overwhelmed with violence and adolescent injuries every weekend – Friday and Saturday nights – and the same thing is true all around the country. What I would like you to do is to meet with some of these kids and to think through the problem and, if you can, come up with some recommendations for how we might deal with it." I read everything there was to read about violence, and thought about it for a while, and we wrote some grant proposals. There were some practical implementations to deal with people who are chronically violent.

But in the course of doing the work on chronic violence, I began to read the literature on biological psychiatry, because it was my belief that chronic violence exhibited a pattern comparable to that exhibited by chronic criminality. Chronic criminality is a term used to describe people who are chronic offenders. It turns out that maybe 85% of all of the crimes committed that are listed in the FBI's Uniform Crime Reports are committed by a very small number of people – 10-15% of all the people who are ever arrested. So, in other words, there's a kind of a power law that describes these things.

My guess was that the same thing was true of chronic violence: that there were a few chronically violent offenders. And as it turns out, I was right. So we wrote up a number of things about that. But I was thinking about this in the context of post-traumatic stress disorder. If ten percent or so of the population were doing all of this violent crime, there had to be some unifying feature that caused it in this group. And although there were a number of correlates, the most significant one, to my mind, was that 90 percent of the people on death row for committing homicides admit to having been molested sexually or abused physically as children, and that probably underestimates the true number.

What I learned in looking at the literature on post-traumatic stress disorder was that a new biological understanding of this had come about in the period between about 1980 and 1985, mostly at Harvard in the trauma lab run by Bessel van der Kolk, and it had to do with endogenous opioids and norepinephrine. But as soon as I read the first phrase in which endogenous opioids appeared, something clicked *(snaps his fingers)*. I recalled that I had just written this book about strong interactions, and here there appeared to be a naturally occurring substance in the brain, which was heroin-like and, hence, might explain some of these addictive features to interaction and attachment that I had been writing about.

So I immediately began looking into the literature on endogenous opioid peptides and I discovered that they had only been discovered in 1972 at Johns Hopkins in the labs of Solomon Snyder, who turned out to be somebody I had met when I was an undergraduate there. I had met him also because Dean Green lived in Baltimore for a number of years, saw Snyder, and went to his synagogue; so I went down there a couple of times and, at one point, ended up meeting Snyder and we exchanged stuff.

I got fascinated by opioids and began to read all the literature on them. Beginning in about 1979-1980, the implications of the discovery of opioids for understanding patterns and behavior began to be spelled out, particularly in research on other species, monkeys and puppies. But some of it pertained to attachment and I looked into this stuff and as soon as I read it, I knew that it was something I needed to get my brain around, which wasn't too hard, since it's fairly straightforward, but the hard part was figuring out what to do with this information.

In biological psychiatry and neuroscience literature, and what is now called social neuroscience, experiments had been done that reported correlations between this and that, opioids, something else, etc. But these guys were just recording correlations and effects. But I figured that to make use of it, to study what I wanted to study, you needed to model it. So I began to think about how to represent what was going on formally.

My first pass at this took place in 1992 or so in one of the things I did on chronic violence, and then I wrote a piece in 1993 or 1994 for *Social Psychology Quarterly*, which is the big social psychology journal in my field about catastrophes and interaction. Catastrophes are nonlinear; they're disjunctive events in nature that can't be modeled in the usual linear kinds of thinking that scientists employ about continuous forms of variation.

I began to think about the toddler – the toddler sort of moving away from his mother's knee and suddenly turning around and coming back and holding on. To me, this seemed to be a clear example of the toddler taking over responsibility for tuning these brain systems, because what happens is that attachment by a mother to her child, if the child is in distress, causes the release of these calming opioids in its brain and Mom also gets a fix. She picks the baby up, she gets opioids as well. But the toddler is moving away from Mom and toward Mom, and moving away is comparable to Mom moving away from the baby, which causes the opioid system to shut down and the arousal system to kick in.

So on one hand, you've got opioids at high levels when Mom is attached and then when Mom separates, you get high levels of activity in the arousal system of noradrenalin and norepinephrine or other hormones and things that are part of the arousal system called the HPA axis. The idea was to model a kind of reciprocal dependence between activity in the arousal system and activity in the opioid system, in terms of the behavioral controls over those two systems.

This mystified me for a long time. How I was going to do this? But I had figured out what the model should look like, and it turned out to have a formal logical structure akin to something in chemistry that is called a hypercycle. Hypercycles are linked autocatalytic sets or cross-catalytic and autocatalytic sets, sets in which a reaction occurs and there is a reaction set in which a feedback mechanism is present that will stimulate the mechanism to continue. So you have two of these, these cycles as they were, and they sometimes get linked together because the byproducts of one or both of these two cycles will play a part in the other reaction set. So then you have two linked cycles – those are called hypercycles – and they stay linked together because the dynamics in these linked causal arrangements are stronger than the dynamics of the two separated reaction sets.

So the argument is that you get strong molecular interaction that produces a more complex structure, and the strong forces keep that structure in place. This is actually an argument for how life emerged – an argument about how simpler chemical reactions combine to produce more complex chemical reactions, and you get more complex and highly organized systems working on the basis of simpler ones.

The argument I began to make was that something comparable to a hypercycle was at work in interaction, and that it entailed a cyclic reaction set involving brain opioids, attachment behavior, and withdrawal symptoms that arise in relation to fluctuations in opioids, and another cyclic system that arises in relation to the arousal system.

Separation is the typical form of behavior in the infant-caregiver system. You get separation stimulating the arousal system, and then you also have a form of withdrawal in that system that has to do with downward fluctuations in the level of norepinephrine. So you get two forms of anxiety – two forms of distress. The opioid system distress surfaces in babies because babies communicate their distress – they cry. When they cry, Mom picks them up, and this causes opioid to be released, which leads to withdrawal symptoms being read. Then Mom can relax; she goes away, opioid system shuts down and the adrenaline level kicks up. So you have a link-causal arrangement.

I knew this was the formal structure of the system, but I didn't quite know how to model it until one day when I was sitting in my office with a couple of students and we had been brainstorming on this. I said: "Let's put up some reasons on the board that seem to describe what we are talking about here." I wasn't particularly happy, and then I saw something that one of the kids (Greg Stevens) was putting up, and I said: "Whoa, stop right there… that's a population question."

As soon as I said that, I realized that the logic of population biology could be used to describe the things that we were talking about. All we had to do was consider the brain chemicals as populations, so that you had populations of opioids and populations of norepinephrine, and those populations would fluctuate. They would fluctuate under conditions that are governed by population biology models. Essentially, we are talking about the opioids competing for attachment behavior in this sort of behavioral niche, and the arousal system competing with the attention behavior for separation behavior.

That was the deep insight, a moment of genius, (*laughs*) – I thought so, anyway. As soon as I saw that, we had a mathematical apparatus that had been well developed which we could use to model these reactions. So, we began to do that. We decided that we would use computational methods to study the mechanism. We would get computational data, and the data would then be interpreted.

The problem would then be to make sense of the data. We can do simulations and computations until the end of time, but you have to do them intelligently. What we decided to do was design a number of experiments that would allow us to see how distress fluctuated in a system of interaction under different conditions that we could specify. One of the main parameters in the population biology model that we were using is a parameter that we likened to intellectual and cognitive development. Since we can manipulate this parameter in these models, it's as if we were growing a child. And as we grew the child by changing the value of this parameter then running these computations, we would see vastly different dynamic patterns emerge.

It became clear that there were only some conditions under which interaction would stabilize; they basically had to do with reciprocity, but also with a number of other variables. So we did that piece, which I think was a fundamental rethinking of the category of altruism and reciprocity from a biological perspective.

The second thing we did was to move beyond looking at two people and to try to model what happens in social networks. I wrote a piece with Greg Stevens called "The Architecture of Small Networks," which has turned out to be a seminal piece in the new literature on networks; everybody likes it. They began to see for the first time that you can compute the properties of social networks bottom-up on the basis of generative models that are rooted in the neuroscience of the species – what I call the neurosociology of the species. The people who study social networks in my discipline have taken heed of this kind of work, but there have been many developments in network theory in the last ten years, and they have a life quite apart from my little project, brain and interaction.

That's where my work is now; I have done what I think I need to do with the old version of hyperstructures, which we now call "Ye olde hyperstructures" (*laughs*), and have moved on to new models of how this all works by deepening the thinking to more fundamental levels, and bringing in a lot of other hormones and neurotransmitters that we had – well, we hadn't ignored them, we'd worked on testosterone and dominance in the early stuff; that was very, very interesting, where we simulated dominance arrangements in the family system in small networks. But now we are talking about new models of networks that are likened to synapses, synaptic models. What we have concluded is that the hyperstructure in the old version, as modified to take into account some other chemical players, is actually a mechanism that forms synapses socially, which is an interesting idea.

So we have moved beyond the old stuff and what we really want to do is to study large-scale networks with these synaptic kinds of models. They're much more complicated, and they're going to entail some formidable new mathematics and computation, but that's where we think we need to go. And the work has caught on; there now are people who like this stuff on the brain and behavior everywhere. I got invited last year to give a plenary address at some national meetings, and this year I've been invited as a guest of the International Sociological Association to go to Rome in July to deliver an address to all the people who will be there, which will be shocking to them. Europeans don't know about this sort of thing.

jur: Your research spans all these different fields of chemistry, biology, neuroscience, sociology. Have you encountered any difficulties in trying to combine these different fields into your research?

Smith: Well, the danger is of simplifying work that has been done in other areas, and, of course, what we do with the neuroscience side of it is to vastly oversimplify the underlying complexity of the brain. But we try to do so without distorting the underlying processes. I think the original versions of hyperstructures were gross oversimplifications. But I still think that they are right; it's just that all the things that needed to be drawn into those models weren't there. And, in part, because we began thinking about those things in 1990 or so, and in the period between 1991 and 2004 – opioids, although they are still extraordinarily important, and endorphins and whatnot – although they are still a major field of study, they have taken a side seat next to some other main players, and the understanding of pair bonding and attachment behavior in other species, and probably in the human species as well, mainly oxytocin and vasopressin, which are two related hormones – men have a lot of vasopressin and women have a lot of oxytocin. So, we began rethinking everything with the idea that opioids and the oxytocinergic system and vasopressin all work together as redundant mechanisms, and there's some sense in which that's true.

The real danger is when somebody at the macroscopic level, which is what I'm working at, begins to try to understand physiological considerations and how social behavior is rooted. The real danger is simplifying the physiology so much as to make it unrecognizable. We've tried not to do that. And the constraint on me, of course, is that I have to write stuff that people who have no training in neuroscience can read; so there's obviously some simplification that goes on, even though we try at the same time to develop the model to the level of complexity that would be satisfying to the neuroscience people who read them or the physiology people.

I remember one of the first papers that I submitted to a sociology journal – they kept that piece for two years, before they finally decided to reject it. And they had all these neuroscientists reading it. Some of them were very, very supportive, and one thought it was so promising, as a matter of fact, that he said he was the editor of the physiology journal and he said "I think you should submit this to the physiology journal." It's interesting! It's a theoretical model, but if you get it into a biology journal somewhere, you will perhaps attract interest on the part of the neuroscience people to do some experiments with this kind of thing.

Anyway, that journal that rejected this piece was the American Journal of Sociology, which is published at the University of Chicago, my alma mater, and I sent it to the American Sociological Review instead, which is actually the leading journal in the field, and they published it. So yeah, the danger is simplification, and also so overstretching yourself that, you know, you can become an amateur in everything.

But I'm fascinated by the theory, and the stuff that we do has taken on a life of its own. Every empirical subject to which I have turned these models has been opened up by this kind of fresh thinking, so that it has led to new understandings of these things. So it's an inducement to continue to work with these models; it's exciting, new horizons appear all the time. You're drawn on by the excitement of exploring the model.

jur: Where do you see the field moving to?

Smith: Well, there is going to be resistance on the part of social scientists to any forms of reductionism. It persists in sociology, especially, and I'm certain in economics and political science as well; less so perhaps in psychology. But it persists in sociology because one of the turf-wars from which sociology emerged as an academic discipline was fought by Emile Durkheim in the French University system at the turn of the century. And Durkheim, in order to establish the legitimacy of sociology as an independent academic discipline, began inquiries into a number of subjects, like suicide, which he felt and claimed had a kind of ontological status, that he could describe in terms of what he called social fact, by which he meant that there were forms of variation in these things that could not be reduced to subsidiary levels of analysis, and that could only be accounted for by other social facts, other things that occur at the level of social organization.

So, sociology has proceeded since Durkheim with the doctrine that much of the subject matter is irreducible. And I have attacked Durkheim's writing, making me a heretic by claiming that putting his imprimatur on things does not expand our understanding of things but limits it; and, so, that's heresy among sociologists (*laughs*).

But I began to win people over to my point of view, and as I started to say a minute ago, I love my field, I love sociology, I just love the history of it, and I love what sociologists study; I just think it's absolutely fascinating, I love the people in it, I love the intellectual puzzles. It's not simple, it's very complicated stuff, and the field has been dominated by empirical work by people trying to measure things very carefully and to establish reliable measurements of this, that, and the other thing, and establishing covariation and causal relationships and all that sort of things, and that's great science, and I love that.

But I think the field is going to die; it's going to be eclipsed by work undertaken in adjacent fields unless it takes a biological turn. So I feel that part of the motive to my work is that there's this sort of moral urgency to reform my field, to get people in my field to think more biologically… and I'm getting an audience. I also get hate-mail (*laughs*).

jur: So there's been some resistance, then?

Smith: There's been resistance, yeah. A lot of what I publish in professional journals though is too complex for the typical non-quantitative sociologists to understand. So, I have tried to write a number of simple arguments, versions of the arguments which I put out in various places. Those are widely read now; the technical stuff has been appropriated in a number of areas. The work on networks is taught in network courses at the leading places, you know, Stanford, Chicago, and Harvard.

Resistance is everywhere, resistance to reductionism. See, I'm a strong believer in the view that any scientist has to be both a reductionist and an emergentist [sic]. You have got to seek to find explanations for whatever it is you are studying at more fundamental levels of analysis, but insofar as those are unavailable, insofar for example as more complex forms emerged that are irreducible, then y0ou need to be an emergentist and acknowledge the fact that there are reasonable and separate subjects that constitute a different level of analysis. But it makes a lot of people uncomfortable to hear that work that they have undertaken without any attention to what's going on in neuroscience might partly be understood in terms of implications of activity in various brain systems for understanding interaction and behavior.

I say if anything social is mediated by interaction, and thinking – interaction and communication – if anything social is mediated by that, that means every subject in the social world has got to heed the forces that are at work in social interaction. From my point of view, the core dynamics of social interaction are driven by physiological forces and they are the things we can see in the most elementary forms of interaction, what I call the minimal social system, which is the mother and the infant, the newborn.

jur: Is there any way for undergraduates to get involved in sociology research?

Smith: Of course. I would say there are many opportunities to undertake research of the sociological kind. There are sociologists here and in the medical school; not too many, but there are some. And there are sociologists on campuses around here; some of them work with me. So all kinds of subjects are open.

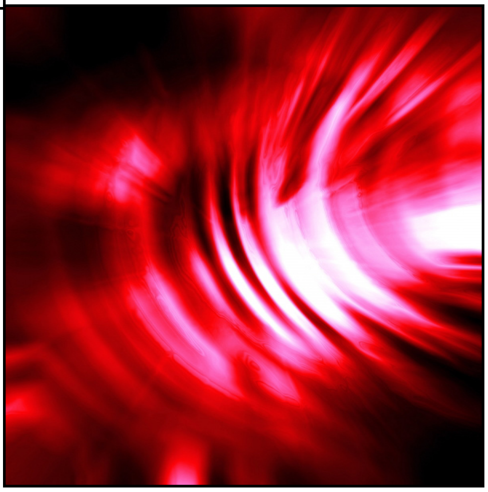
I have undergrads who are working with me on all kinds of things right now. Several of them own computational work, those who have learned to program. I've trained and sent off to graduate school a handful of students over the last 5 or 6 years. My former students are at Cornell, Michigan, UCLA, Chicago, and Harvard these days. And they carry the message (*laughs*). They've gone off to the very good schools. I have a former student who is an associate professor at Geneseo, who is doing a post-doc with me starting next year; she plans to try to measure some of these things by brain scanning.

But for students who want to work with me, I encourage independent research; but if they want to get involved in a research project, they have to know how to program. If they know how to program, we'll set them up.

jur: What advice could you give to undergraduates that are thinking of pursuing a career in research?

Smith: Learn as much math as you can and as much programming and statistics as you can as an undergraduate, because you need to lay down basic disciplines before you start in graduate school. My philosophy of education is that when you get out of this you need to have learned how to read, write, and count better than you could when you came in. The counting part turns out to be very, very important if you're going to go on to do scientific research.

The thing is, research has changed a lot; nature now is being tackled in its full complexity – well, maybe not its full complexity, but with an eye on the real complex organization of natural systems, instead of as in the past, when scientists had limited computational resources available to them and they would simplify things. You would try to work in little packages that were parts of wholes, and you tried to figure out what was going on in those parts with linear equations. Of course, nothing is really linear, so what you need to learn is nonlinear differential equations (*laughs*) and some statistics, and if you can program, computational skills always come in handy.



Shear Viscosity under Shock-Loading Conditions

Zhuohan Liang[1] and Steven M. Valone[2]

[1]T-4, Los Alamos Summer School
[2]MST-8, Los Alamos National Laboratory

Although we rarely see a shock wave in everyday life, we experience them upon hearing the sound of an explosion, the bang of a gunshot, or the crack of a whip. In addition, objects that travel at supersonic speeds, such as bullets and missiles, also generate shock waves. During a typical shock-loading process, large pressures generated at the shock front can lead to an increase in the reactants' reactivity via decomposition, as well as changes in mechanical and structural properties. Consequently, the initiation of shock waves often changes the nature of a reaction and, therefore, its final products.

In a fluid's case, we can study the impact of a shock wave through variables that describe physical properties of the materials on both sides of the shock front, i.e. density, temperature, and particle velocity. As a result, shear viscosity, which measures a system's resistance to flow as a function of the relative velocity of adjacent layers of particles, is changed drastically under shock-loading conditions.

More specifically, when a fluid is shocked, particles behind the shock front experience both a compressive force and a shear force, which together push particles away from their original equilibrium positions. In this process of deformation, shear viscosity largely depends on the speed of the relative movements between adjacent layers of particles. To describe this type of shock-activated process, we need to solve the momentum conservation equation, i.e. the Navier-Stokes equation,

$$(1)\quad \rho\frac{\partial v}{\partial t} = -\nabla p + \eta\nabla^2 v$$

and identify an accurate model of the fluid viscosity η. In Eq. (1), ρ is the density of the fluid, v is the velocity of the fluid particles, p is the momentum of the fluid particles, and η is the shear viscosity of the fluid. By definition, η is the ratio of the shear stress in the shear rate,

$$(2)\quad \eta = \frac{f}{\dot{\varepsilon}}$$

where f is the shear stress, and ε is the shear rate and equals $\Delta V/\lambda_1$. In the expression of ε, ΔV is the velocity difference between two layers of particles that are a distance λ_1 apart. Based on the difference between forward and backward rate constants, Eyring proposed that

$$(3)\quad \Delta V = 2\lambda k_1 \sinh\left(\frac{f\lambda_2\lambda_3\lambda}{2k_BT}\right)$$

where λ_2 is the distance between neighboring molecules in the direction of motion, λ_3 is the molecule to molecule distance in the plane normal to the direction of motion, and λ is the distance between equilibrium positions. k_B is the Boltzmann constant and T is the absolute temperature of the reactants.[1] Based on this relation, our study aims to give a better estimate of shear viscosity, which in turn tells us the type of fluid motion, laminar or turbulent, that is occurring behind the shock front.

A brief review of the historical development of Eyring's shear-rate dependent model for viscosity would be helpful. In 1935, Eyring proposed the formula

$$(4)\quad k_{Eyring} = \frac{k_BT}{h}\frac{Q^+}{Q_{RCT}}e^{-\frac{V^+}{k_BT}}$$

for the activated rate processes based on Transition-State Theory (TST), where Q^+ is the partition function for the particles at the transition state, Q_{RCT} is the partition function for reactants. V^+ is the barrier height, and h is Planck's constant.[2] During the following year, he extended the result to calculate viscosity, which inherits the assumption of TST that particles in both the reactant well and the transition state are in thermal equilibrium. For many years, Eyring's viscosity formula has been used for all chemical reactions, regardless whether they satisfy TST's thermal equilibrium assumptions. As a result, many applications of the TST model to reactions under shock-loading conditions gave inaccurate predictions. Indeed, Valone showed in his 2003 paper that applying shock to a material drastically increases its reaction rate to several orders of magnitude higher than rates calculated under thermal equilibrium assumptions.[3] Based on this model, our current study concentrates on adjusting Eyring's shear-rate dependent model for viscosity to account for changes in reaction rate under shock-loading condition.

We will present arguments for using Valone's model for shock-activated processes. First, we will analyze the conditions for thermal activated processes, and explain why TST are suitable for those processes. Then, we will discuss the differences between thermal and shock activated processes, and why the assumptions of TST are no longer applicable to reactions

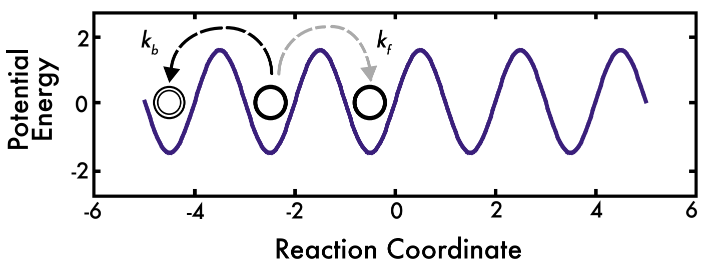


Figure 1:

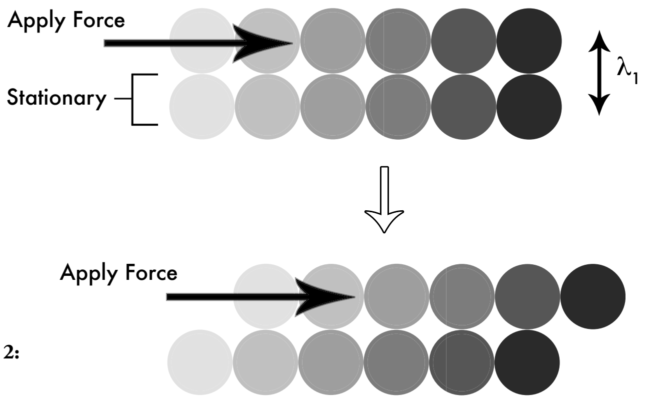


Figure 2:

under shock-loading conditions. Finally, we propose two main modifications - reaction rates under shock-loading conditions and velocity dependence of shear rate - to the TST model for viscosity. We also include primary comparisons between the TST model and the new model for viscosity.

Transition-State Theory Kinetics

When a system of particles is in thermal equilibrium, each one of them is equally likely to go forward or backward on the reaction coordinate, as shown in Fig.1. However, when there is an outside force, one direction is favored, as shown in Fig. 2. During this process, momentum is conserved. The dissipation of momentum depends on viscosity, which expresses the motion of the particle in terms of the rate constant k_1. This k_1 is in the same form as the reaction rate in TST.

The conventional TST was developed through a series of studies that started in 1889 by Arrhenius and fully developed by Eyring in 1935. To describe a system in reactions, the TST assumes that it is always possible to carry out coordinate transformation so that variables relevant to the current reaction are on one reaction coordinate, while all other coordinates are perpendicular to this reaction coordinate, as shown in Fig. 3.

Along the reaction coordinate, which is not necessarily a linear one, TST says that reaction rates are determined by the dynamics of the reactants as they pass through the potential barrier to the product well. Implicitly implied by this statement is the assumption that the system is at equilibrium at each point of the reaction coordinate. In particular, particles at the transition state and the reactant well need to be in equilibrium respectively. If these assumptions are satisfied, concentration at the transition state can be calculated by using a Boltzmann distribution. Specifically, the velocity distribution is Maxwellian.

In a thermal equilibrium, multi-dimensional system, the TST predicts that particles in the reactant well will always follow the lowest energy path to get to the product well. Fig. 4 shows sodium-fluorine and helium-fluorine reaction in a two-dimensional potential surface. Under thermal equilibrium conditions, particles go through the saddle point into the product well. However, under shock conditions, the amount of kinetic energy they acquire may dominate the thermal effect, so if the shock wave is in the same direction as the thermal reaction coordinate, the shock will facilitate particles going into the product well. However, if the shock points toward an unfavorable direction with respect to the thermal reaction coordinate, particles will be pushed onto reaction paths other than the thermal one and end up as different products. In this two dimensional picture, one can clearly see that in fact products in shock condition are different from those in thermal condition.

If we try to express this physical situation mathematically, we get the reaction rate constant from the following equation

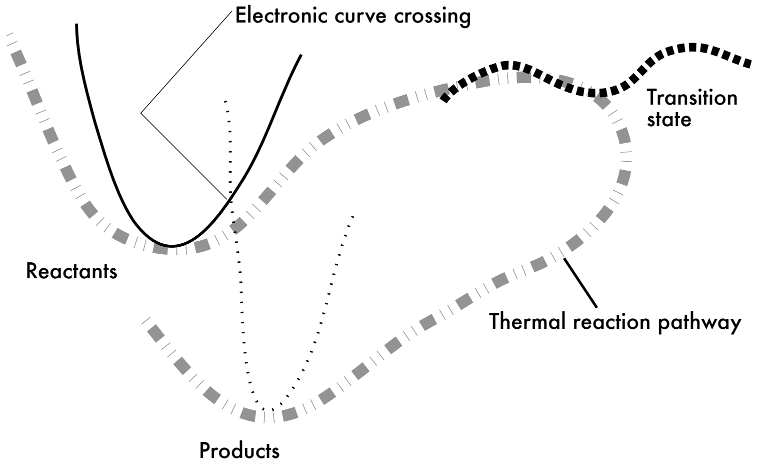


Figure 3:

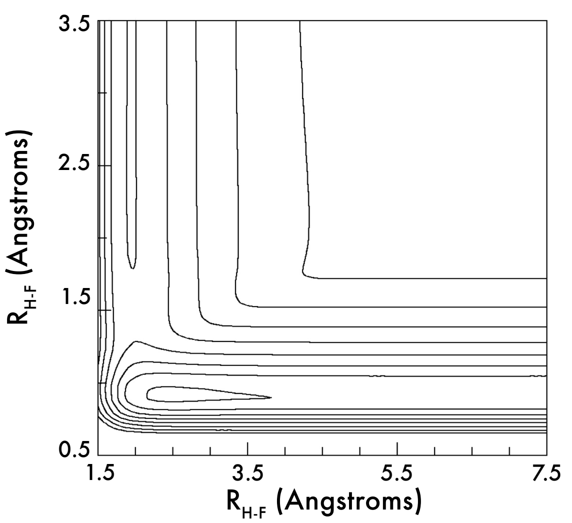


Figure 4: By Maria S. Topaler and Donald G. Truhlar, J. Chem. Phys., **108**, 5350 (1998).

$$(5)\quad k_{Eyring} = \frac{\int \delta(f(q-q^{+}))\nabla f \cdot u\,\theta(\nabla f \cdot u)\, e^{-\frac{H(u,q)}{k_B T}}\, dudq}{\int \theta(-f)\, e^{-\frac{H(u,q)}{k_B T}}\, dudq}$$

where q is the multi-dimensional coordinate of the reactive particles, q^{+} is the coordinate of the reactive particle at the transition state, and u is the multi-dimensional velocity. H is the multi-dimensional Hamiltonian of u and q, $\frac{1}{2}mu^2 + V(q)$, where $V(q)$ is a potential. m is the mass of the particle. $\nabla f \cdot u$ is the particle velocity perpendicular to the dividing surface at the transition state. The delta function in $q - q^{+}$ confines the numerator to the region near the barrier top where $V^{+} = V(q^{+})$. The Heaviside-step function θ applied to the velocity ensures that only particles moving in the direction of the product well of the potential are counted as having passed through the flux-counting surface. The Heaviside-step function θ in the denominator confines the particle to the well region.

The TST works well in multi-dimensional systems. However, a system is frequently simplified into one dimension to facilitate calculation. In one-dimension $V(q)$ becomes the potential of mean force along the reaction coordinate, and u is the velocity along the reaction coordinate.

As explained earlier, under shock-loading conditions the actual reaction often deviates from the thermal reaction coordinate, and so continuous use of Eq. (5) will give an incorrect prediction of the reaction rate. In his 2003 paper, Valone proposed that TST can be altered by re-centering the velocity distribution at the transition state around the projected particle velocity on the reaction coordinate. The application of this idea yields astonishing effects. The rate constant in the improved model is many orders of magnitude greater than the thermal reaction rate. Indeed, when an atom immediately behind the shock front collide with unperturbed material immediately ahead of the shock front, the reaction rate would depend on the projected-shock velocity instead of some effective temperature, as shown in Fig. 6. Furthermore, beyond a critical projected-shock velocity relative to the barrier height of the reaction, the kinetic rates saturate and increase with a weaker dependence on the shock speed.

The new reaction rate constant now can be expressed as

$$(6)\quad k_{shock} = \frac{\int \delta(q-q^{+})\, u\,\theta(u)\, e^{\frac{-H(u-u_q,q)}{k_B T}}\, dudq}{\int \theta(q^{+}-q)\, e^{\frac{-H(u-u_q,q)}{k_B T}}\, dudq}$$

In this expression, uq is the projected particle velocity, while other variables are as defined above. When kinetic energy of the shocked particle is less than the barrier height, i.e. $\frac{1}{2}mu_q^{2} < V^{+}$ Eq. (6) can be simplified as

$$(7)\quad k_{shock1} = \frac{\omega}{2\pi} e^{-\frac{V_u^{+}}{k_B T}}$$

where $u_q^{+} = 0$, and $V_u^{+} = V^{+} -$. However, when kinetic energy of the shocked particle is greater than barrier height, i.e.

$$(8)\quad k_{shock2} = \frac{\omega}{2\pi}\left(e^{\frac{-m(u_q^{+})^2}{2k_B T}} + \frac{u_q^{+}}{2}\sqrt{\frac{2\pi m}{k_B T}}\, erfc\left(-\sqrt{\frac{m(u_q^{+})^2}{2k_B T}}\right)\right)$$

where $u_q^{+} = \sqrt{u_q^{2} - \frac{2V^{+}}{m}}$, and $V_u^{+} = 0$. Further examination of Fig. 6 also shows that, as expected, particle-velocity dependence is washed out at high temperature.

Viscosity at shock front

Assuming that Valone's model of shock activation holds for shear processes, we now consider the shear process that takes place under shock-loading conditions in a fluid.

As the shock front passes through, particles are compressed in the same direction as the propagation of the shock wave. We also notice that right at the shock $\frac{1}{2}mu_q^{2}$ there is a force pushing particles away from the center of the compressive wave. This is the shear force that appears in shock-loading conditions. Apparently, the shear process depends on the strength of the

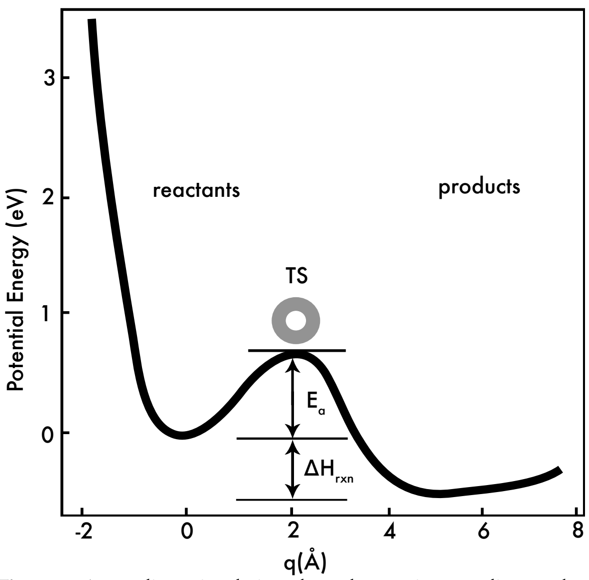


Figure 5: A one-dimensional view along the reaction coordinate, where particles need to have activation energy E_a to get onto the top of the potential barrier and into the product well.

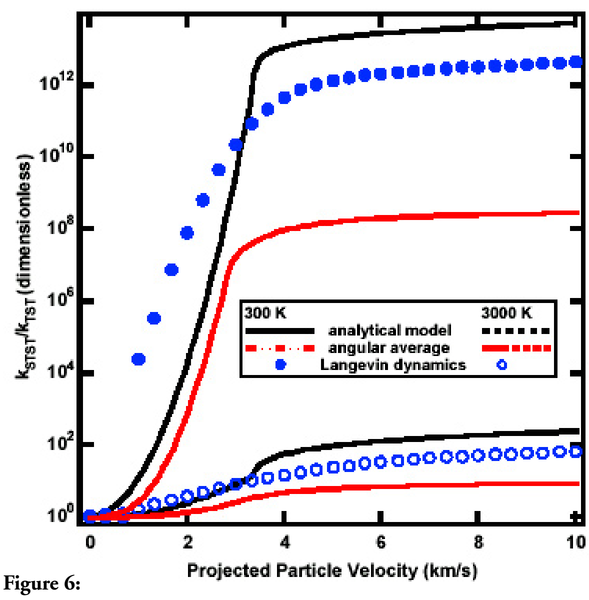


Figure 6:

shock, which is manifested in the velocity of the particles behind the shock front. In 1988, Holian suggested

$$(9)\quad \dot{\varepsilon} = -\frac{u_p}{\lambda_H}$$

to express the relation between particle-velocity and shear rate, where λ_H is the shock-wave thickness and is equivalent to λ_1 in Eyring's expression. He also proposed the empirical relation between viscosity and the Reynolds number in shock-loading conditions to be:

$$(10)\quad \mathrm{Re} = \frac{\rho_0 u_s \lambda_H}{\eta}$$

where ρ_0 is the density of the unshocked material, u_s is the shock-front speed. Eq. (10) suggests that viscosity is a main factor in determining the magnitude of Re, which tells us whether the flow inside a material is laminar or turbulent. This means that the particle-velocity dependence in viscosity can potentially change the character of the flow.

We put previous reasoning into mathematical expressions as follows. We first apply Valone's shock TST to the shear process in shock-loading condition to modify the rate constant in Eyring's viscosity model. In order to do this, we need to correctly interpret each variable in Eyring's definition of viscosity in terms of variables that appear under shock-loading conditions. This is accomplished by relating Eyring's viscosity to our normal understanding of Newton's law of viscosity in Eq. (2). With reference to Bird, Stewart and Lightfoot[4], who propose that

$$(11)\quad f = A\,\mathrm{arcsinh}\left(\frac{1}{B}\dot{\varepsilon}\right)$$

Newton's form of viscosity can be written as $\eta = \frac{A\arcsin h(\frac{1}{B}\dot{\varepsilon})}{\dot{\varepsilon}}$

To cast Eyring's formula into the same expression, we rewrite Eyring's f in terms of η, so that

$$(12)\quad f = \frac{\eta \Delta V}{\lambda_1}$$

Substitute Eq. (12) into Eq. (3), we get η as a function of ΔV and λ_i's, but not f. The result is

$$(13)\quad \eta = \frac{2k_B T\lambda_1}{\Delta V \lambda_2\lambda_3\lambda}\arcsin h\left(\frac{\Delta V}{2k_1\lambda}\right)$$

$\dot{\varepsilon} = \frac{\Delta V}{\lambda_1}$ is in the same form as η from Newton's theory. Since , we can rewrite Eq. (13) as

$$(14)\quad \eta = \frac{2k_B T}{\dot{\varepsilon}\lambda_2\lambda_3\lambda}\arcsin h\left(\frac{\dot{\varepsilon}\lambda}{2k_1\lambda}\right)$$

We further consider that in Eq. (14) the shear rate should depend on particle's shocked speed, instead of being a constant for all different shock strength. Therefore, based on Holian's argument[5], we substitute Eq. (9) into Eq. (14) and finally arrive at

$$(15)\quad \eta = \frac{2k_B T}{u_p\lambda_2\lambda_3\lambda}\arcsin h\left(\frac{u_p\lambda_1}{2k_1\lambda^2}\right)$$

for the viscosity. To compare viscosity $\frac{2k_BT}{u_p\lambda_2\lambda_3\lambda}$ r shock and thermal conditions, we cancel the prefactors , and arrive at

$$(16)\quad \frac{\eta_{shock}}{\eta_{Eyring}} = \frac{\arcsin h\left(\frac{u_p}{2k_{shock}\lambda_1}\right)}{\arcsin h\left(\frac{u_p}{2k_{Eyring}\lambda_1}\right)}$$

Result

We first compare viscosity at different temperatures and different barrier heights. Since shear rate is now written as a function of particle velocity along the reaction coordinate, its effect on viscosity is determined by changes of particle velocity. Fig. 8 is our primary comparison between the new model and the thermal-equilibrium model of viscosity at the same barrier height but different temperatures. As expected the new shock-loading model of viscosity is several orders of magnitude smaller than the thermal model. We expect that this dramatic decrease in viscosity may bring the Reynolds number to the critical value by which different flow regimes are determined.

We also tested the new model at different barrier heights. Each one of the plots in Fig. 9 shows that the new model of viscosity is very sensitive to particle-velocity. At zero particle-velocity, the two models of viscosity give the same prediction. However, as velocity increases, viscosity decreases exponentially and then becomes linear. One may also observe that in each of

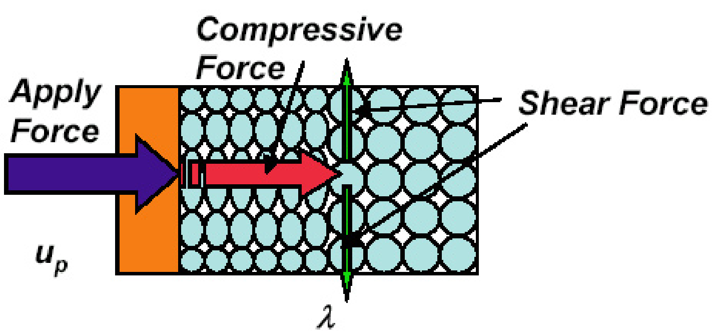


Figure 7: A piston is used to compress a volume of fluid particles.

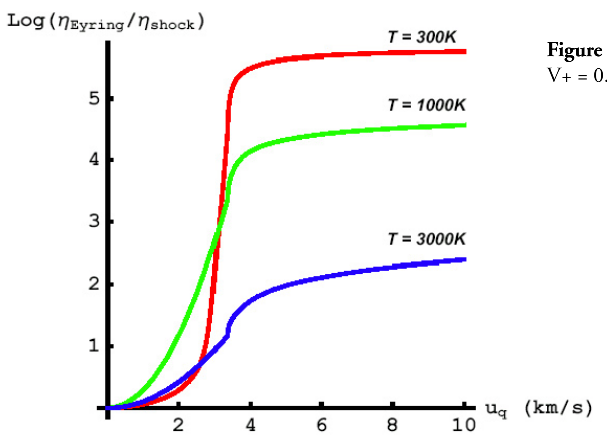


Figure 8. Constant V+ = 0.7eV.

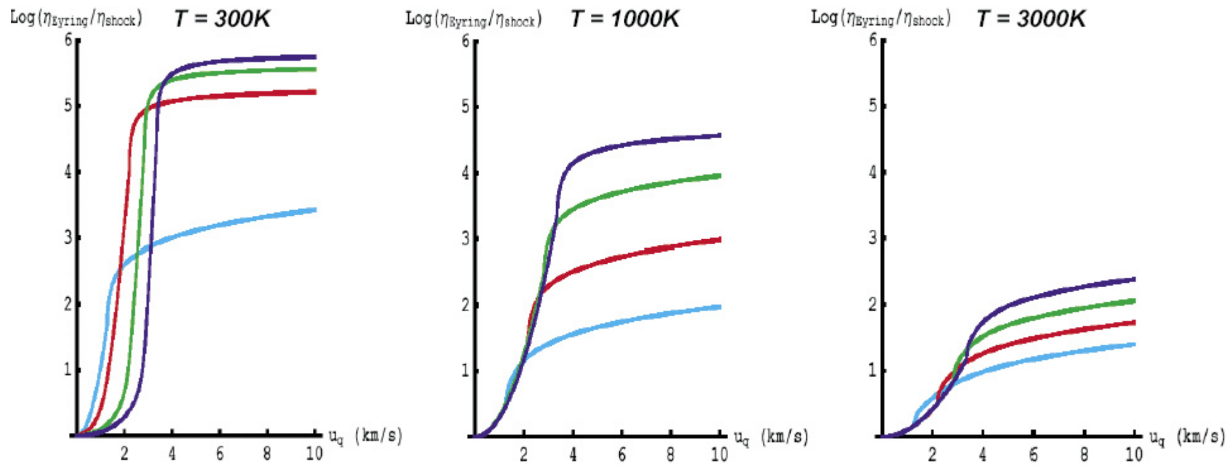


Figure 9. (Cyan) V+ = 0.1eV, (Red) V+ = 0.3eV, (Green) V+ = 0.5eV, (Blue) V+ = 0.7eV.

these plots, viscosity shows the same wash-out effect at high temperature as the chemical rate constant.

Conclusion

So far, we have analyzed some of the changes in the dynamics of a shock-loading material, in particular the effects of increasing particle-velocity in chemical reaction rates and their implications to the calculation of shear viscosity. As shocked particles acquire much greater kinetic energy compared to the system's original thermal energy, they follow a different reaction path than the thermal one. Indeed, the reaction rates under shock-loading conditions are orders of magnitudes greater than the thermal reaction rates.

The current standard model of viscosity is based on Eyring's thermal equilibrium TST model. To incorporate what we know from the above analysis, we propose to modify the TST model of viscosity under shock-loading conditions in order to account for higher reaction rate and particle-velocity dependence of shear rate. Initial computational tests of our model showed that the thermal equilibrium model of viscosity gives too high a prediction for viscosity in shock-loading conditions. In fact, our model of shock-activated viscosity gives values which are different enough from Eyring's model to change the flow regime. That is, a material originally expected to experience a laminar flow might in fact experience a turbulent flow. The difference will in turn lead to different predictions of the mechanical and structural properties of the material.

In order to obtain more conclusive information on the effects of shock waves on shear viscosity, we expect to test the new model with a computer simulation of viscosity under shock-loading conditions.

Acknowledgements

I would like to especially thank and acknowledge Dr. Valone for the copious amount of his time, advice, patience, insight, and guidance. This work was supported by the United States Department of Energy ASCI Program, the National Science Foundation, and the University of New Mexico. Acknowledgement is also due to Dr. Magee, Dr. Collins, and Dr. James for their invaluable support of the Los Alamos Summer School.

1. Eyring, H. J. Chem. Phys. 4, 283 (1936).

2. Eyring, H. J. Chem. Phys. 3, 107 (1935).

3. Valone, S. J. Chem. Phys. 118, 6289 (2003).

4. Bird, R W. Stewart, and E. Lightfoot. Transport Phenomena, John Wiley & Sons, Inc.(1960) 3-29, 34-48, 154-161.

5. Holian, B. Phys. Rev. A. 7, 37 (1988).

Zhuohan Liang graduated from the University of Rochester in May 2005 with a B.S. in Physics, a B.S. in Mathematics (both with highest distinction), and a minor in Philosophy. She was named a Barry M. Goldwater Scholar and a Take Five Scholar during her last year at the college. She is currently working toward her Ph.D. in physics at Johns Hopkins University. This article grew out of her work with Dr. Steven Valone at Los Alamos National Laboratory in the summer of 2003. She was given the award of Outstanding Undergraduate Oral Presentation in Materials Science at the Los Alamos National Laboratory Symposium that summer.

Featured Researcher

Fault Tolerant Behavior-Based Robots

Laura Wong, 2008

Advised by William Wong, MS
Department of Mechanical Engineering

This Featured Researcher article focuses on Laura Wong, a member of the Class of 2008, majoring in Mechanical Engineering. She first became interested in robotics at an early age when her father introduced her to computer technology. Through computer technology, she advanced to robotics engineering and programming. She has participated in Intel's Science and Engineering fair since 2002 and has won various awards including an Intel Computer Science Award. After completing her degree, she plans to work in the robotics field, specifically with homeland security and safety robotics.

What is robotics research all about?

Robotics research has a wide variety of topics –from medical robotics to toy robotics. My main research involves search and rescue robotics using sensors and fault tolerance. The military and many security companies use search and rescue robotics to save and preserve lives. For example, if there is a suspicious cave, one could send in a robot to search the cave for any hazardous or dangerous object/people instead of sending in a human. If it turns out that there is indeed something hazardous in the cave, they will only lose a robot, which can be remade, and not someone's life. Robotics research is widely used to help humans in many ways.

Who or what motivated you to start on this research project?

I began working in the field of robotics the summer before my freshman year in high school. I became interested in robotics a few years prior to that, when my siblings were playing with a toy robot they received as a gift. With the addition of my father working with computers, I began to develop interest in computer programming. With the support and motivation of my father and the rest of my family, I stuck with robotics throughout my high school career. Throughout the years I gained knowledge of different sensors used for robotics. For my final project, I incorporated everything from the mechanics aspect to the computer programming aspect, which I learned over the years.

While doing this research project, what do you think was your biggest obstacle and how did you overcome it?

This particular research project took about 9 months to be completed. Over the course of 9 months, I encountered some minor obstacles such as power supply and wiring confusion. Each robot ran off of 8 separate C batteries, but the problem was that they would only run about 10 minutes at a time. Aside from that, there are many different wires in each robot that connect everything together and if one became loose it was a slight challenge to figure out what came undone. The main obstacle I had to tackle, however, was to learn the programming language of JAVA, which was completely new to me. Over the years I have worked with BASIC, C++, and Pro-Log. Working with a variety of these programming languages can be quite confusing when you are writing a program due to the fact that many of them are closely related to each other. But with a lot of determination and even more patience I was able to grasp JAVA.

After completing your research project, what do you think was your most fulfilling experience?

After completing this research project I participated in a national science fair held in Mercer County, New Jersey, where I received the Grand Award. By winning the Grand Award, I was able to participate - for my third consecutive year - in Intel's International Science and Engineering Fair, held in Portland. There I participated in a weeklong science fair where I was able to present my project to a variety of judges and to the public. I received second place in the Computer Science group and a variety of special awards. The main award I was most proud of was the top award from the United States Army, which included a medal, $3,000 in savings bonds, and a two-week trip to London where I participated in an international science forum with 250 young scientists from all over the world.

Any advice you can give to fellow undergraduates who would like to do this kind of research?

The main advice I can give to fellow undergraduates is to not get discouraged when something doesn't work the first, second, or third time. Robotics is a very complex area and you need to start at the basics to get a slight grasp on it. It would also be helpful to find a mentor who knows a lot about the area. Having a mentor over the years made my experience more valuable and allowed me to get used to the field of robotics more easily. Finally, allow your family and friends to take part in the experience - having support from many people makes the experience easier and gives you boost to continue on with your research, especially when you are faced with obstacles.

Swarm robots, a collective of cooperating robots, provide a way to apply many devices to a problem. Utilizing many robots brings a level of redundancy that improves overall fault tolerance — where a system continues to run possibly in a degrade mode when a fault occurs.[1] They can also provide mutual application support such as providing positional references to each other,[2] as well as increasing the range of the overall system compared to a single robot.

Creating software that addresses fault tolerance can be difficult, but one way to simplify this task is to use meta-behaviors within a hardware system designed with sensors and resources with overlapping capabilities.

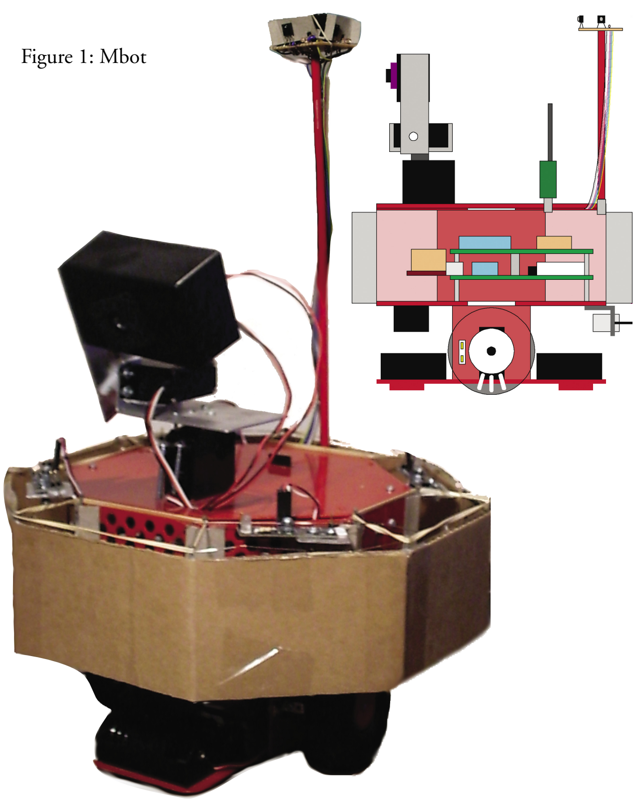
A variety of behavior-based programming methods have been used over the years.[3] The robust nature of behaviors allows behavior-based robots to handle the inaccuracies of sensors and resources. Plan-based solutions that try to use techniques like dead reckoning and accurate maps[4] tend to run into accuracy problems the longer they run.

Behavior-based programs are usually easy to create and modify, although the techniques for designing and testing tend to be different from many other programming tasks because of the way behaviors interact. Behaviors are invoked dynamically so the interaction between behaviors, which compete for system resources, is often not explicitly stated in the design making testing. This is a key part of a system's implementation.

Behavior-based systems can be implemented on very small computing platforms[5] such as the Mbot used in this paper and shown in Figure 1. Behaviors tend to be relatively simple requiring minimal storage. Systems that exhibit complex actions can be created with less than a dozen behaviors.

Behaviors typically use a set of inputs to control how

Figure 1: Mbot



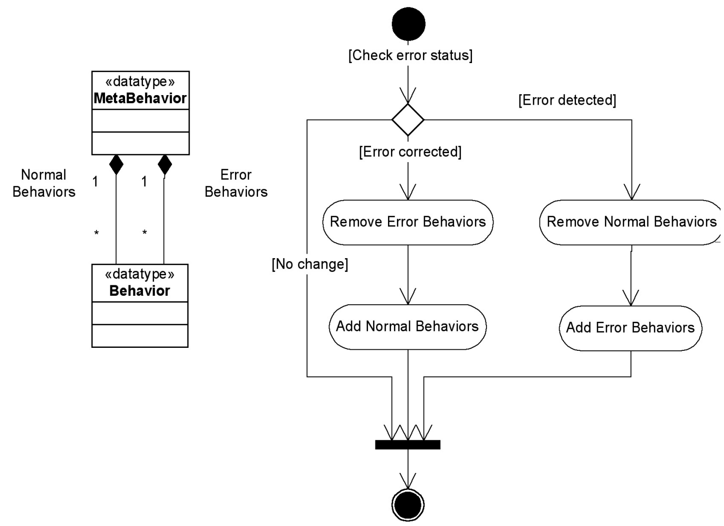


Figure 2: Fault-tolerant Meta-behavior Architecture

resources are used.[3] For example, an obstacle avoidance behavior may stop the wheel motors of a robot when the input from a touch sensor indicates the robot has collided with an obstacle. A different behavior may cause the wheels to move forward if there is no obstacle. Yet another may cause the wheels to turn the robot towards a goal such as a light source.

One technique for determining which behavior gains control of a resource is called subsumption.[6] In this case, behaviors can inhibit inputs or suppress outputs of other behaviors. Another technique is called motor schemas,[3] where weighted outputs from behaviors are combined to control a resource. Typically, the behavior with the highest weight has the greatest impact on a resource's action. Behavior prioritization is yet another technique[5] where priority can be implemented in a number of ways, such as keeping behaviors in priority order and using the first behavior on the list that wants to use a resource.

Many behavior-based systems determine what behaviors to use by repeatedly scanning a list of active behaviors. The cycle time determines how quickly the system, in this case a robot, responds to changes in the system's environment. This approach is used in this paper. Minimizing the cycle time improves the system's responsiveness.

Meta-behaviors fit into this cycle-style approach very easily. The key difference between a behavior and a meta-behavior is the kinds of inputs that are used and the actions performed by the behaviors. For our purpose, a behavior uses system inputs and manipulates system resources while meta-behaviors use information about system inputs and resources to manipulate behaviors.

Figure 2 shows how a typical fault-tolerant meta-behavior operates along with its main components. In general, a meta-behavior contains a list of normal and error behaviors. When a fault is detected, it removes any normal behaviors and replaces them with behaviors that will address the problem. The process is reversed if the fault is corrected. The meta-behavior may initiate other corrective action when a fault is detected allowing the fault to be corrected.

The figure uses Universal Modeling Language (UML) diagrams to describe this process. UML is used in other

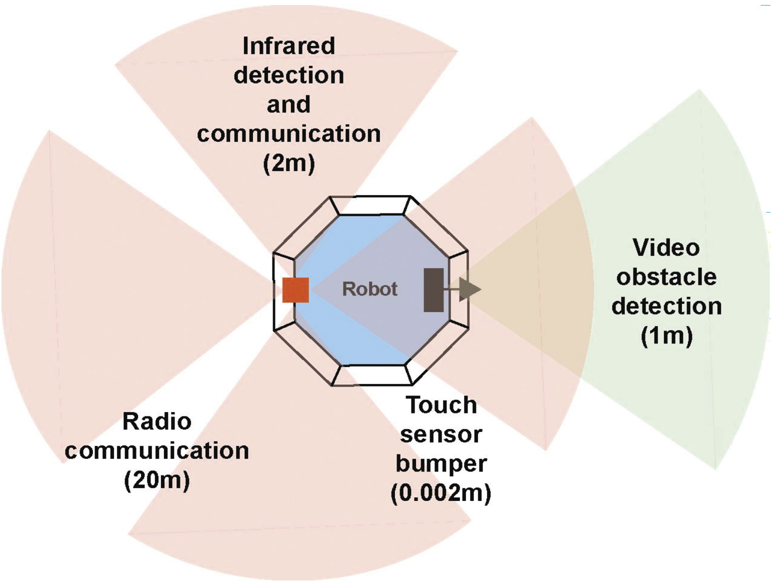


Figure 3: Overlapping Sensors And Resources

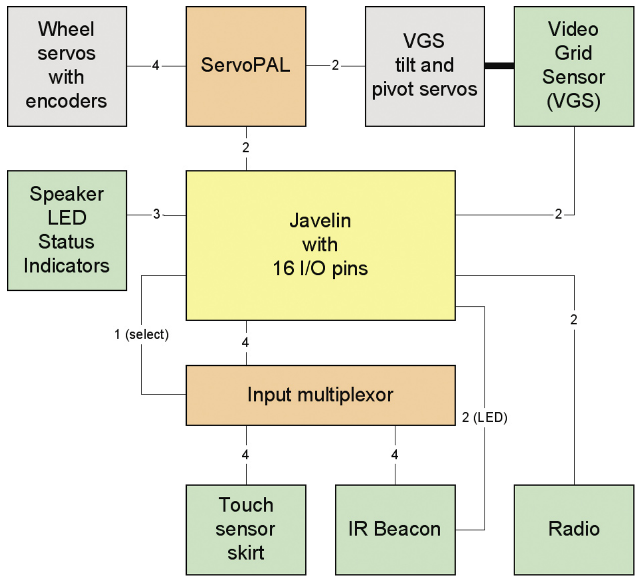


Figure 4: Mbot Block Diagram

diagrams such as state charts and sequence diagrams within the paper. The explanations within the paper should allow anyone unfamiliar with UML to understand the diagrams.

Fault tolerance has been implemented in other fashions such as creating behaviors that explicitly take faults into account.[7] This approach works but it can lead to more complex behaviors. It also tends to use many active behaviors whose overhead can impact system performance.

Fault tolerance is easier to achieve if there is some level of redundancy in the hardware. In a swarm, numerous instances provide redundancy--assuming the loss of a robot is acceptable. Replication of a particular subsystem, or providing sensors and resources with overlapping capabilities, is another way to provide redundancy within a robot. The latter was chosen as a way to make the Mbot a more robust system. It also made it easier to initially test the meta-behavior approach using a single robot when one of the subsystems was disabled.

Figure 3 and Table 1 show the complement of sensors and resources employed in the Mbot. The Mbot uses a Video Grid Sensor (VGS). The VGS is an intelligent camera I developed.[8] It uses color information to locate obstacles and identify objects by color. This allows other robots to be color coded for identification.

The Mbot can continue functioning even if one of these resources is disabled, although it may not be able to perform useful work if more than one subsystem fails. Another subsystem not listed is the wheel motor control. If these fail, the robot cannot move, but it could still provide a readily identifiable landmark to other robots within a swarm. Meta-behaviors and error behaviors can be created to make this happen.

Materials and Methods

This section addresses hardware and software architecture employed, the test environment, and the types of tests used to exercise the architecture. As with most robotic experiments, the hardware, software, and environment are restricted to minimize overall complexity. This is especially true for systems with limited resources.

Robot Construction

The Mbot is a custom robot. The main hardware subsystems are shown in Figure 4. The Java-based, Javelin microcontroller is the centerpiece, although there are a number of other microcontrollers within the system. These include the ServoPal, which is used for servo control, and the video grid sensor (VGS).

The Mbot has a pair of drive wheels. It can pivot on its center axis. Wheel encoders make more accurate movement possible in addition to providing odometer information.

Obstacle avoidance is handled by the VGS and the touch sensor skirt (Figure 5) that surrounds the Mbot. The VGS only provides information about objects in front of the Mbot, although it can tilt and pivot the camera providing a wider and longer range of vision compared to a fixed camera. The VGS provides simple image analysis designed to deliver a compact image map to the Javelin via a serial port.

Name	Communication	Range	Orientation	Angular Coverage	Obstacle Detection
Radio	Yes	20 m	No	N/A	No
IR Beacon	Yes	2 m	Yes	360°	IR beacon
Video Grid Sensor	No	1 m	Yes	90°	Yes
Touch Sensor	No	0.002 m	Limited	360°	Yes

Table 1: Mbot Device Input And Communication Capabilities

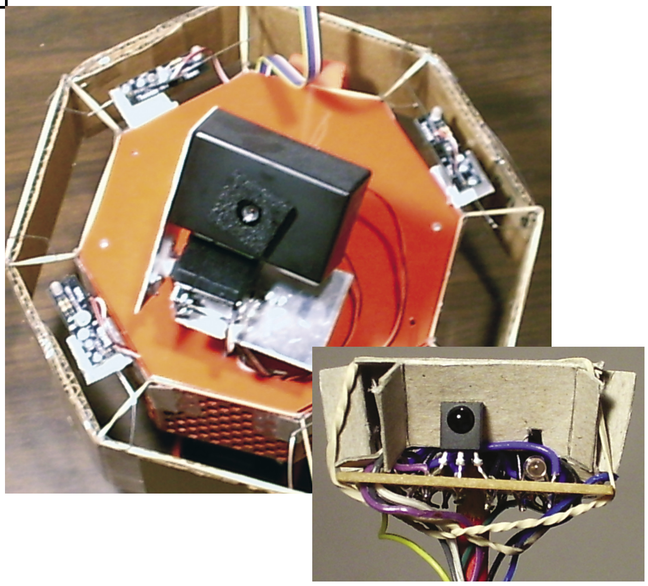


Figure 5: [left] Touch Sensor Skirt. **Figure 6:** [right] Mbot IR Beacon.

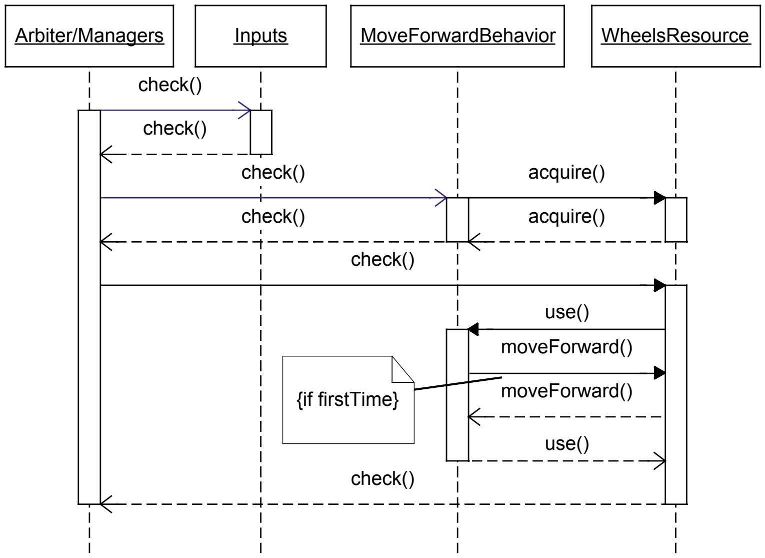


Figure 7: Simple Behavior

The IR beacon shown in Figure 6 provides limited orientation information allowing the Mbot to locate another beacon within 45°. It can also exchange serial information with another beacon at low speeds. The radio transceiver also provides a non-line of sight communication link to other robots. It is faster and more accurate than the IR beacon communication.

The Javelin has a number of limitations that significantly impacted the design of the system. First, it only has 32Kbytes of memory for both program and data. Using intelligent peripherals like the ServoPAL and VGS reduces the size of behaviors and supporting program code. Second, the Javelin has only sixteen I/O pins. The intelligent devices make better use of the pins and a multiplexor chip helps cut down the number of inputs required.

Memory was not the only software limitation. The Javelin implements peripheral interfaces using virtual peripherals that are allocated from memory. There is a limit of six active virtual peripherals (VP). The timer service uses one of the six active VP slots. Table 2 shows the list of VPs used in the system.

The total number of VPs exceeds the five available active VPs so it was necessary to activate and deactivate VPs as needed. This tended to slow down the operation of the robot because it was often necessary to stop movement or other actions while active devices where changed and used.

Type	Name	Description
Serial	Radio in	Wireless serial communications
Serial	Radio out	
Serial	Beacon in	IR-based serial communications
Serial	Beacon out	
Serial	VGS in	Control link with VGS
Serial	VGS out	
Serial	ServoPAL	Bidirectional link with ServoPAL
PWM	Beacon PWM	Pulse width modulation for IR beacon
Timer	System Timer	Used to manage Timer objects

Table 2: Javelin Virtual Peripheral Utilization

Software Architecture

The system employs a single tasking, priority-based arbiter to support the behavior-based system because the Javelin does not support multitasking or garbage collection. Three list managers keep track of the three major items: inputs, behaviors, and resources. Input objects provide status information about the Mbot and its environment. The behavior list contains all active behaviors and meta-behaviors. Resources are controllable subsystems. The primary resource is the wheel servos.

The first thing the arbiter does is check all inputs. Each input should store its current information so all behaviors that test an input will see the same information. Changing this information on the fly instead will cause all sorts of problems. A behavior may check any number of inputs. An input object may provide a range of information.

If a behavior meets its internal conditions it will then try to acquire any necessary resources. The highest priority behavior will be allowed to use a resource. The arbiter checks all resources after it checks the behavior; a resource will notify a behavior if it can use it. It will first tell any behavior that may currently be using the resource if a higher priority resource needs it. This allows a higher priority behavior, such as, avoiding a collision, to take control of the robot's movement.

Figure 9 shows a simple behavior in a simplified diagram. The Arbiter/Managers column condenses down the arbiter and list manager interaction of Figure 8 into a single transaction. The MoveForwardBehavior causes the robot to move forward regardless of whether an obstacle is in front of the robot. This allows another behavior to check for obstacles. The robot starts moving forward the first time the WheelsResource is acquired.

The behavior in Figure 10 shows a more complex ballistic interaction. The detection of an obstacle starts a movement sequence in which the robot stops, backs up, and then pivots to one side so it is no longer facing the obstacle. It then releases the wheel resource allowing another, lower priority behavior like the one shown in Figure 9 to take control. If there is still an obstacle in the way then the behavior in Figure 10 will gain control and the process will be repeated.

Test Environment

Since the Mbot has limited mobility and the VGS has limited accuracy, it was necessary to control the test environment. The VGS is also sensitive to some lighting conditions. For example, bright sunlight will overwhelm the camera and incandescent lights emit IR radiation that can limit its accuracy.

The test environments consisted of rooms with an open area of 4m x 5m. The floor was flat with tiles or low pile carpet. The VGS was able to handle variegated floor colors. The light was fluorescent with minimal shadows. The skirts of the robots were color coded so they could be identified using the VGS. This allowed an Mbot's VGS to recognize another Mbot even if the IR beacon failed.

Objects had a different color than the floor and the Mbots. They were tall enough to come in contact with the touch sensor skirt. Objects were at least 0.5m apart if the Mbot was expected to go between the objects. This distance was sufficient for the Mbot to move through the area and for the VGS to recognize the opening.

Tests

Two major goals were used to drive the creation of the behaviors. The first was to Find and Face another robot. The second was to Follow the Leader robot. Figure 12 shows how this occurs and the behaviors and actions performed. The follower robot wanders until it finds the leader. It needs to be within range of the leader to recognize it. The follower was placed near the leader so it did not have to wander too far. This was done to minimize the time needed to complete an experiment.

The first step was to create a set of behaviors to allow the Mbot to handle each task under normal operating conditions. The second step was to develop meta-behaviors that could detect errors in subsystems. The third step was to generate error behaviors that operate with a subset of inputs and resources. Finally, the normal, error, and meta-behaviors were combined and tested.

The combined behaviors were tested by simulating a fault. For example, a VGS fault was simulated in software. It was also simulated by disconnecting its serial communication link and by covering the camera lens.

Results

Behaviors and meta-behaviors created were sufficient to perform the tasks presented. Development of error behaviors proved to be straight forward since it was possible to test a small subset of behaviors. For example, a more advanced approach to find the leader uses the VGS to stay a short distance away. A simpler approach without the VGS is to use the touch sensors. In this case, the robots came in contact. A third approach is shown in Figure 13. In this case, meta-behaviors to handle a follower robot VGS fault are found in both robots. The meta-behaviors and error behaviors are different for both robots but they do cooperate. The overall system performance is lower

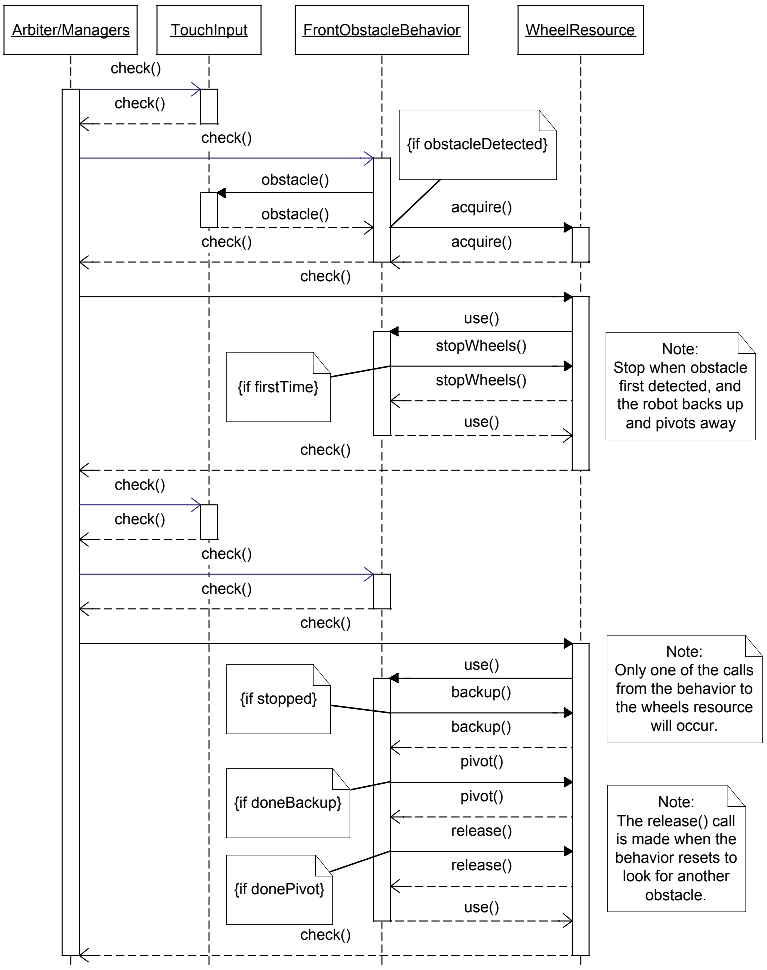


Figure 8: Complex ballistic behavior

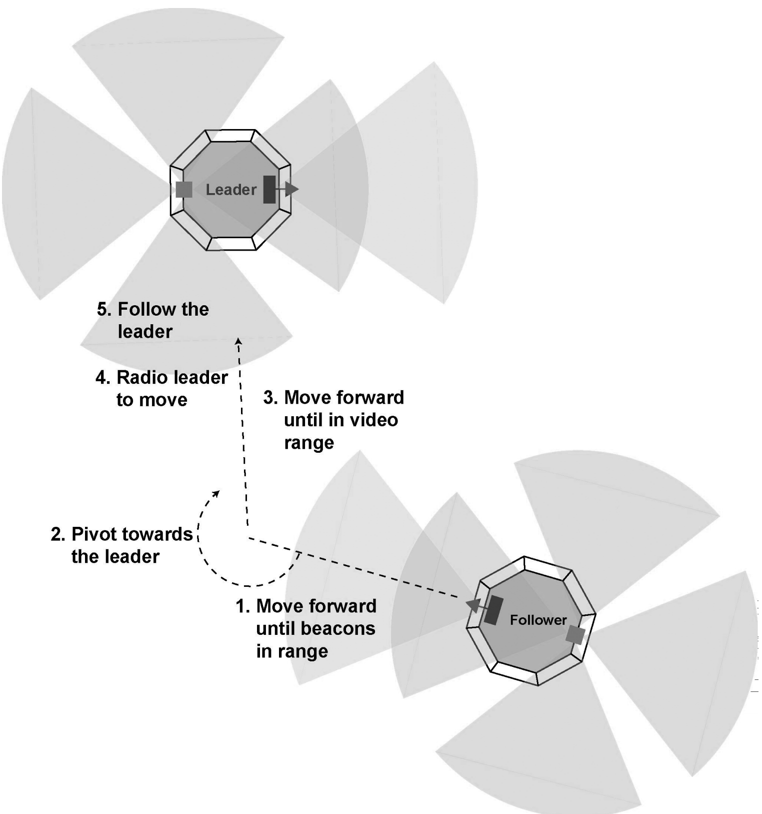


Figure 9: Homing robots using normal behaviors

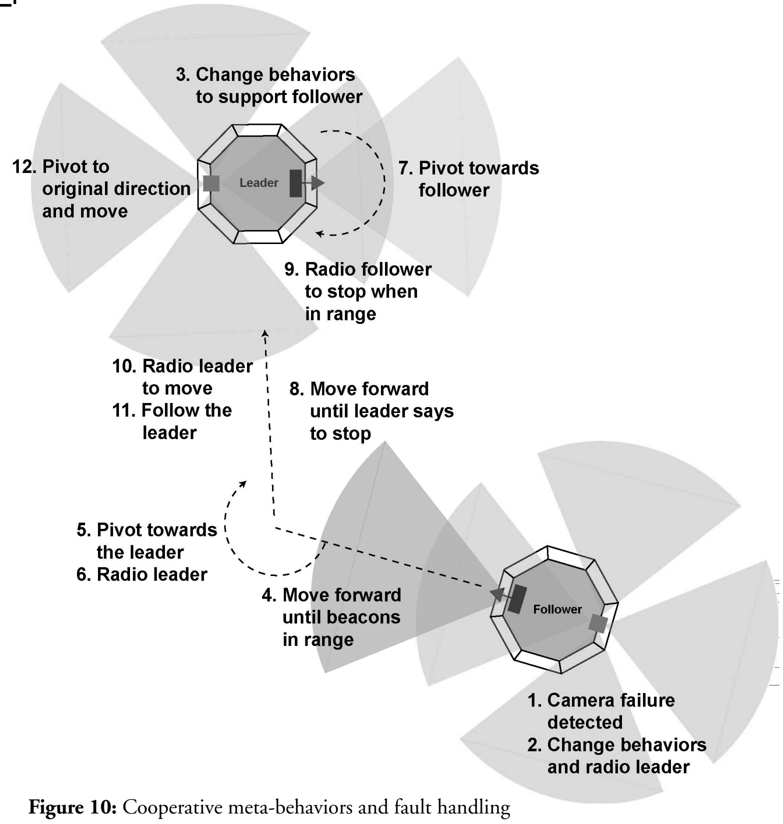


Figure 10: Cooperative meta-behaviors and fault handling

than when the follower robot VGS is working but the results are still useful.

In the case of the leader robot, the meta-behavior waits for a message from a follower robot. It then added a set of error behaviors that face the follower and communicate with it so the leader's VGS can be used to determine when the follower is close enough. The process significantly slows down system operation because the leader had to face the follower then later turn away to move forward and finally turning back again. Still, writing the error behaviors needed to perform this task was a straight forward process.

The meta-behavior on the follower had both normal and error behaviors. Testing was easy because the error behaviors for the leader and follower could be loaded and tested independently of the normal behaviors. In many cases, the set of error behaviors included normal behaviors created for other tasks.

System overhead for meta-behaviors did not add too much overhead because the input tests were usually simple go or no-go decisions. Simple subsystem self-test operations were fast. One difficulty was trying to determine that the VGS was not working when the lens was covered because the condition was similar to having the robot in an open area. Two solutions to detecting this fault seemed to work well. The first was to indicate a fault if the front touch sensor indicated an obstacle and if the VGS had not detected any obstacle since it was started. The second was to indicate a fault if an initial self-test tilted the VGS up so it could scan the horizon after determining what the floor color should be. The self-test takes awhile, so it significantly slows down the robot if the test is done while the robot is performing other actions.

Discussion and Conclusion

The meta-behavior approach to solving the fault tolerance problem worked well in this instance especially with sensors and resources with overlapping capabilities. Having two communication systems allowed testing of cooperative solutions to faults, although the performance was severely but not completely degraded. The inclusion of the touch sensors was critical to the robot's ability to detect objects it could not see using the VGS and for determining when the VGS may have failed.

Unfortunately the touch sensor design was prone to needing readjustment. The sensor worked well once the four sensor contacts were checked, but they could easily be altered if the robot was picked up and moved from one site or position to another. A different design will be considered in the future.

Most of the testing was a success. The robots successfully completed each task assigned to them. The creation of the behaviors necessary to perform the task was relatively simple compared to the overall system design. A good deal of time was spent on refining the arbiter, inputs, and resources. Memory constraints limited the complexity and number of behaviors that could be loaded at one time, although some space could have been conserved by removing debugging information. Still, the system implementation was sufficient to prove the concept.

The system was able to handle a dozen behaviors, but when they were doubled, the system ran into more memory constraint issues than performance issues. Still, the overhead for checking this many behaviors was high. Certain programming concessions were made, such as using the ServoPAL to run the wheels to cover a fixed distance instead of waiting until an obstacle was detected. It prevented the robot from going too far if the arbiter cycle time ran too long. This could sometimes occur when a meta-behavior was checking an input for a fault and the test took more time than the typical sensor testing process.

One problem encountered in previous projects was the speed and performance of the robot. This was not a problem this time, except when a fault was detected and a lower performance was expected in this instance. The ability of the robots to move and search at the same time was primarily due to the use of ServoPAL and VGS coprocessor. Handling the VGS interaction asynchronously also helped. This was done by initiating a VGS operation immediately after the VGS results were obtained. The VGS processing occurred concurrently with the rest of the arbiter cycle.

Meta-behaviors did reduce the number of behaviors that were active at one time. It also simplified the creation of error behaviors. Eliminating the meta-behaviors and combining and enhancing the normal and error behaviors so they handled faults was more complex than anticipated, resulting in more active and larger behaviors. Performance was no better and often lower than the meta-behavior approach.

As noted in the Results section, testing provide to be easier using meta-behaviors. Testing a smaller number of combinations is almost always easier than testing a larger number of combinations.

There was not sufficient time or memory capacity to attempt to use meta-behaviors for planning or to implement high level plans created externally, but the results from using this approach for fault handling indicates that the approach would be useful. It is an area worth investigating.

Other issues arose as the number of behaviors increased and the tasks became more complex. First was the concept of a meta-input and a generic fault meta-behavior class. A standard fault meta-behavior object would have a standard interface to a meta-input object to test for a fault. Therefore adding most fault support would consist of creating a subclass of meta-input for a particular input or resource, and then filling in the normal and error behavior lists of a standard fault meta-object. Second, there was no way to track what behaviors were actually removed when a meta-behavior switched between fault conditions. This could result in restoring a behavior that was not previously removed because it was removed by another meta-behavior. An approach to solve or at least identify this condition will be found in the future. Third, the use of changeable, numeric priorities for behaviors eliminated the need for dealing with sorted priority schemes and allowed resources to be managed independently when necessary. For example, one behavior may be using the radio resource while another is using the wheels. It provides a sort of multitasking within behaviors.

Another area of study would be the use of multitasking arbiters and multiple arbiters in a more complex system that has subsystems with minimal interaction. For example, a robot with two arms may work better with three arbiters for the robot movement and each arm with meta-behaviors coordinating the interaction between subsystems.

Meta-behaviors can easily be implemented as standard behaviors but formalizing the process makes it easier to deal with and allows the reuse of common services, like adding and removing the lists of behaviors when a fault occurs. They definitely made programming the Mbots easier.

1. Drenner, A., et al. "Design of the UMN Multi-robot System." Multi-Robot Systems: From Swarms to Intelligent Automata. Schultz, A.C., and Parker, LoE., editors, Kluwer Academic Publishers (2002): 141-148.

2. Howard, A. and Mataric, M.J. "Deployment and Localization For Mobile Robot Teams" Multi-Robot Systems: From Swarms to Intelligent Automata. Schultz, A.C., and Parker, L.E., editors, Kluwer Academic Publishers (2002): 41-52.

3. Arkin, A.C. "A Behavior-Based Robotics." MIT Press (1998).

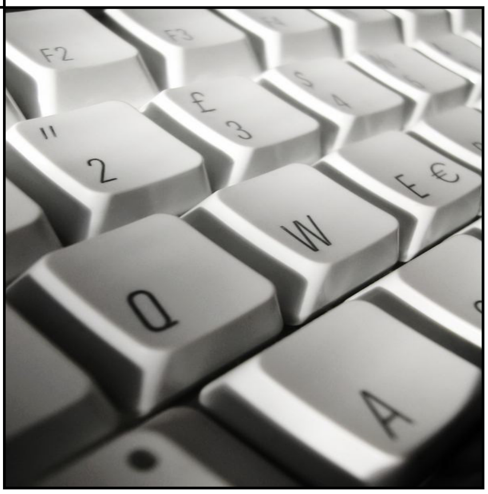
4. Wong, L. "Where Am 1? Minimizing positional error while navigating and mapping using a cooperative robotic system," Villa Victoria Academy (2002).

5. Jones, J. L., and Roth, D. "Robot Programming: A Practical Guide to Behavior Based Robotics." McGraw-Hill (2004).

6. Brooks, R. "Elephants Don't Play Chess" Designing Autonomous Agents. Maes, P., editor, MIT Press (1990): 3-15.

7. Parker, L.E. ALLIANCE: "An Architecture for Fault Tolerant Multi-Robot Cooperation." IEEE Transactions on Robotics and Automation, 14 (1998).

8. Wong, L. "1 See You: Robotic Navigation Using Appearance-Based Obstacle Detection: Villa Victoria Academy (2003).



Continuous Identity Verification through Keyboard Biometrics

Peter Ordal, 2004 David Ganzhorn, 2006
David Lu, 2006 Warren Fong, 2004
Jonathan Blair Norwood, 2004

Advised by Michael L. Scott, Ph.D.

Department of Computer Science

To increase personal computer security, keyboard biometrics is a robust option that uses common hardware. By recognizing differences in key press duration and latency between key pairs, a highly personal profile can be created, which can be used as a unique identifier for an individual. Instead of testing the user's identity once at log in as prior work has done, we focused on continuously monitoring keystrokes in the background from the user's normal typing and using that information to verify the typist's identity. After comparing the typist's current key strokes to the computer's saved profile, the program can challenge the user to verify his or her identity if appropriate. Using segments of 150 keystrokes, we obtained zero false lockouts and only 5% missed lockouts. More keystrokes decrease the percentage of missed lockouts.

Introduction

Biometrics is the science and technology of determining identity based on physiological and behavioral traits. Other physiological biometrics include retinal scans, finger and handprint recognition, and face recognition. Behavioral metrics include handwriting analysis and voice recognition. Keyboard biometrics is considered a behavioral biometric. Behavioral biometrics cannot be falsified without explicitly targeting a particular user and training extensively to match their behavior.

Using keyboard biometrics is a viable means to achieve improved computer system security. Although the data analysis techniques used here do not offer the same level of extreme scrutiny as a fingerprint or retinal scan, they also do not require end users to purchase any special hardware to use, and thus make for a worthwhile security device.

The biometric works because everyone has his or her own typing pattern. At the surface level there are clear differences in overall speed from one user to the next. Some users are heavier upon the keyboard, with long durations and small digrams, which translates to a lot of overlapping key presses. Other users are more "hunt and peck": pressing keys down quickly and then retreating, which would translate to small durations and longer digrams. On a deeper level, each user has a unique pattern as to how quickly he or she presses each particular key, as well as how quickly he or she transitions from one particular key to another. Users vary so much in these unique patterns that they can be used for accurate biometric identification.

Our algorithms for profile creation rely on two data sets: key press duration and key digram duration. Durations are the time that a given key is pressed down, i.e. from key-down to key-up. Typical times range from 70 to 150 milliseconds. Key digram durations are measured from the key-down event of one keypress to the key-down event of the following. These can range from 50 to 200 milliseconds. We found a large amount of variance between users using these two metrics.

Summary of Prior Work

Keyboard biometrics has reached the level of having a noticeable impact on computer security. Specifically, prior work has reached close to 0.01% impostor pass rate (less than 1 successful attack out of 10,000 attempts) and a 4% false alarm rate based on a user group of 154 participants. Up to this point, there have been some hindrances in implementing the work already completed, most notably that 300 characters must be typed for proper comparison to an existing profile. Our goal is to improve on this level of accuracy.

In 1980, R. Gaines conducted experiments with seven secretaries who were asked to retype three paragraphs two times over a four-month period.[1] Keystroke latency timings were collected and analyzed using the specific digrams that occurred during the paragraphs. This means that the two different times were averaged to create a profile for each of the secretaries. The results were very encouraging but the data offered too small of a sample to build an acceptable profile.

Later experiments conducted by John Leggett actually demonstrated identity verification, utilizing and validating Gaines' work.[2] Leggett's work accepted a user if more than 60% of the comparisons were valid. However the false alarm rate was 5.5% and the impostor pass rate was 5%. The problem was that a 1,000 word sample size was required in order for proper comparison of profiles.

Rick Joyce and Goyal Gupta used keystroke information taken during the login process.[3] The system made new users provide reference signatures by typing their username, password, first name and last name eight times, which was used to generate a profile for the new user. Later, the user was required to type his signature, which was compared to the mean and standard deviation of the profile. While this work was very promising, it required extensive profile setup and training of the system. Although interesting research, the practical applications implied here were not realistic.

Fabian Monrose and Aviel Rubin's later paper added onto the previous research. They examined the use of keystroke durations, developed more robust methods for examining the differences between user profiles, studied the use of unstructured text, and incorporated a larger sample set.[4] A Euclidean distance measure was utilized for analyzing the difference between profiles, and a probabilistic measure was the actual deciding factor for accepting or rejecting the user. Utilizing these methods, they managed a 90% correct identification rate.

In 2002, research by Francesco Bergadano, Daniele Gunetti, and Claudia Picardi addressed typing errors and the intrinsic variability of typing. Their experiment used a single text of 683 characters for all participants.[5] Their acceptance/rejection utilized the Degree of Disorder of an Array, the average differences between the units in the array. The false alarm rate of 4% and im-postor pass rate of less than 0.01% are remarkable, but this technique requires a large profile for proper authentication. The research does prove, however, that keyboard biometrics is reliable given a su_ciently large profile. Since this research was designed for authentication of the user at login, as a replacement for passwords, it is not applicable for continuous authentication: this method requires having prior data on the way the user types particular passages.

Our work is designed around building a background process that would actively collect data of the user typing naturally and would use that to build his profile. Once the profile had been built, a security tool would watch for typing patterns that did not fit that profile and simply challenge the user to prove his identity when appro-priate. In this way, we eliminate the need for the user to train the system with artificial text, and do not present significant hurdles to the system-login process. We target casual users who want an extra layer of security and may, at times, forget to lock their desktop systems.

Procedure

Data Collection

We acquired raw keypress data by distributing a standalone Windows application to 42 individuals. This program recorded their keystrokes over the period of several days and reported the data to a central repository via an encrypted internet connection. The smallest profile collected was 3,746 keystrokes, and the largest was 178,392. We offered users the ability to pause data collection and delete recently collected data, in order to ensure only appropriate data was collected. Users' keyboards each used one of two timing intervals for reporting activity: 10ms and 15ms. These data sets are not compatible for comparison. 26 users sent in data with 10ms timing information, so we exclusively used that data in our analyses.

Profile Creation

We turned raw keypress log files into profiles by collapsing data on keypress duration and digram duration. Once a user profile has been created, it can be used to continuously authenticate the person who is typing. We compare the authorized user's profile to a second profile, which is continuously updated from the keyboard readings. To keep the profile current, only a subset of the input is used; the profile is

created from the most recent set of digrams and durations (the set size can be arbitrarily changed), and it is updated every few keystrokes.

Once the two profiles have been created, they can be compared. Our tests have shown that the top 100 digrams (or all available digrams when fewer than 100 are available) and the ten most frequent durations from the current input provide the best grounds for comparison of profiles. These parameters were determined through numerous trials with various parameters; they provided the highest levels of accuracy across various input segment sizes. However, these choices have no formal statistical grounding, and further experimentation may find better parameters.

Profile Comparison Process

The comparison process uses the chi-square goodness of fit test to see how well the individual digrams and durations fit the distribution from the user profile. For example, the timings in the input for the digram "T:H" (that is, pushing 't' and then 'h') would be compared against the timings in the user profile, and the chi-square value would be the result of this test. Because the amount of data gathered within one hundred digrams is quite small, we found that the best way to combine these results into an overall score was to average all of the chi-square values together, but to keep the types of data (digrams and duration) separate. This results in an overall score for how well the input digrams fit the profile digrams, as well as how well the input durations fit the profile durations. Because this score is the average of the chi-square values, and the greater the chi-square value, the less the samples fit together, then the greater the overall score, the worse the fit is between the current user input and the profile input.

Lockout Procedure

To set the threshold at which we lock out the typist, we considered looking at the critical values for the averaged chi-square value to determine the actual probability that the profiles matched. This did not prove to be the optimal approach for several reasons. Firstly, because the majority of digrams in the current input have only one timing and the chi-square test does not give the best probability estimates for such small numbers of examples, the resultant probability would not necessarily be accurate. Also, different users have different amounts of variance for the way that they type; some users are extremely consistent, and other users have a large amount of variance. We wanted to use a method that would allow us to minimize the accepted variance without increasing the false-alarm rate.

The approach we used for finding the minimum variance to accept was more empirical than theoretical. First, we built a user profile from all of the example input we had for the authorized user. Then, we looked at every sequential subset of one hundred digrams and durations within that profile, and compared that subset against the full profile. This allowed us to test all of the typing examples we had for that user against their profile, to see how much their subsets of typing varied in comparison to their overall profile. We then took the maximum of their duration and digram scores, and set them to be the cutoff thresholds. As we noted above, while the program is running, if the current input exceeds either threshold, then the user is locked out.

Measurement of Accuracy

To measure the accuracy of these thresholds, we then ran every other user's data file we had against the original profile. We compared the durations and the digrams separately against the original profile, to obtain the percentage of input segments from other profiles that would be accepted, if either durations or digrams were considered. This gave us distinct accuracy rates for digrams and durations. The current system does not combine the data gathered from durations and digrams in a more sophisticated way. The results of this comparison are below.

This system allowed us to accept all of the variance that occurred within a given user's typing habits (that we have data on), without accepting any additional variance. Also, this process allowed us to empirically measure the accuracy of a given profile. We found this system to be quite accurate and reliable, and we also found that a profile of suffcient size would capture nearly all of a given user's variations. Such a profile could be obtained within roughly 50,000 keystrokes, which should occur within some small number of days, depending on how frequently a person types on their computer.

Completeness of Profile

Currently, we do not continuously expand the profile with

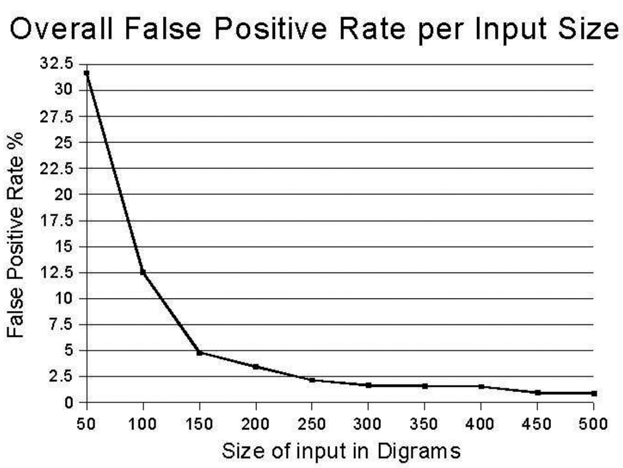


Figure 1:

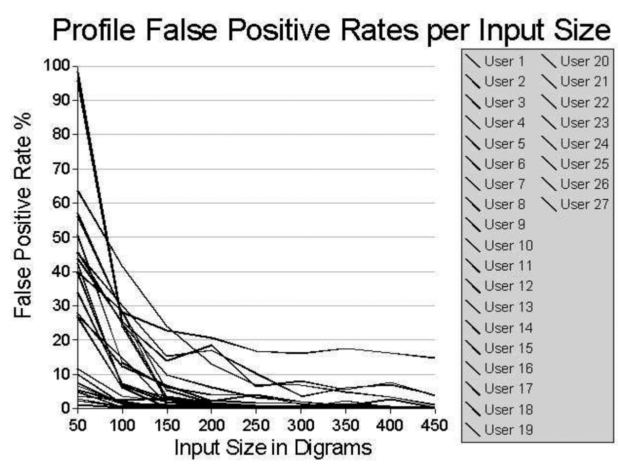


Figure 2:

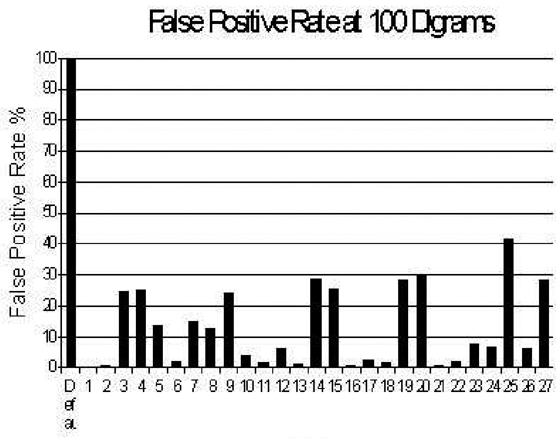


Figure 3:

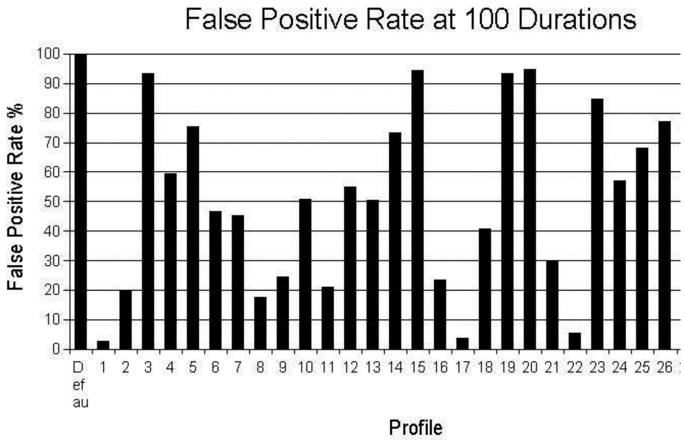


Figure 4:

authenticated input, but this would be a trivial feature to add. However, we have not developed a theoretical understanding of what constitutes a complete profile. It is important to know if a profile is complete or not, as an incomplete profile is going to have a higher false-alarm rate than a complete profile. This would be useful knowledge both for lowering the false-alarm rate while in use, and also to better measure the accuracy of the profiles. Our preliminary idea is to take all of the raw data we have for a given user's typing habits, divide it in half, and compare each half to the other. When both halves accept the other more than a given percentage of the time (say, 99%), then we can be confident that we have captured virtually all of the user's typing habits, and the profile is complete. However, if the user's typing habits slowly change over time, then the profile will eventually become incomplete. We have not found a method to ensure that the profile will remain complete over time, without allowing for variances that no longer occur.

Results

For the final comparison of the results, we ran several round-robin tests utilizing all of our collected data. For the first test, we loaded the 27 user profiles, and then split all of the collected data into 100 digram segments. We then compared every one of these 3,500 segments against each profile. The segments that came from the profile currently being tested were used to set the thresholds for acceptance, and thus a user's own input segments were never rejected. After comparing the input segments from other users against each user's profile, we found the percentage of 100 character input segments from other users that were accepted by each profile. We then repeated this test for 50, 150, 200, 250, 300, 350, 400, 450, and 500 character input segments.

The following graphs show individual profile false positive rates and the overall false positive rate for all profiles. The false positive rate indicates not what percent of users are wrongly accepted, but what percent of input samples from other users are wrongly accepted. In other words, even if a user is wrongly accepted at first, he is increasingly likely to be rejected with each keystroke.

By 150 digrams the lockout rate has reached nearly 95%, and by 500 digrams the lockout rate exceeds 99%.

The point of diminishing returns is around 150 digrams, as further data has a reduced impact on the accuracy of the profiles. The very high false positive rates for 50 and 100 digram segments is a reflection of the very limited amount of data that is available within small segments.

The above are graphs of the false positive rate when using duration data versus digram data, in 100 durations segments.

The much lower accuracy from keypress durations shows how a user's typing pattern for keypress durations is much less characteristic of himself than digram times. However, taking duration data into account in combination with the digram data allows for accuracy to be improved, if only marginally in many cases. For a few users, however, their duration timings are unusually unique, and this data alone results in very high levels of accuracy.

Discussion

The goal of this research was to utilize keyboard biometrics in a real-time non-invasive security system. The system's ability to continuously attempt to authenticate the user based on normal computer usage is vital. The most successful prior work, which utilized login authentication with a pre-determined passage of 683 characters, had a false lockout rate of 4% and an imposter passing rate of .01%. Our continuous user authentication system, when using an input size of 683 digrams from normal computer use, yields a theoretical false lockout rate of 0% and an imposter passing rate of 0.8%. However, the system is subject to the law of diminishing returns, with an increasing number of key stokes needed to lower imposter passing rates. The best performance/data size ratio occurred at around 150 digrams, which resulted in a 95% correct lockout rate. We found that duration data was generally not highly characteristic of individual users, but for a few users it was very unique, and resulted in a false positive rate below 5%.

Usage Concerns

The most often posed question regarding our research has been: won't you falsely lock the user out if she is eating and typing with only one hand? The answer is yes, we will, but that doing so is the correct behavior. We only know about the user's typing patterns based on the data we get. If the user frequently types with a sandwich in one hand, that will become part of her profile and will be accepted. If she types abnormally, however (in the sense that she is typing in some way we have not seen before), the proper response is to challenge her to prove her identity, which is what we do.

Future Work

There are several ways to improve upon this research in the future. Methods of keeping the user profile up to date need to be looked into. Currently, our system can either not accept new typing patterns that the user slowly develops over time, or it will accept them, and also accept old, unused patterns as well. The different outcomes result from whether or not the system will add new verified input to the user's profile. Research into continually pruning and updating the profile may allow for a more optimal solution. However, this would be difficult without keeping around a large key log of the user, which is undesirable from a security standpoint.

The addition of mouse biometrics would increase the uniqueness of each user profile, as well as providing a way to completely secure input-device interactions with the computer; a user can accomplish a lot with just a mouse. Unfortunately, mouse biometrics involves a completely different type of data, as mouse movements are difficult to analyze into discrete, comparable features. Also, our initial investigation into mouse behavior found that a lot of mouse usage behavior is application specific. Future research will have to either look for general mouse behavior features, or a way to catalog mouse behavior for each different application.

Another goal is to reduce the number of keystrokes needed to determine who the user is. The problem is that below one hundred keystrokes, nearly all of the digrams have only one example data point, and it is very difficult to get accurate estimates of whether a single timing came from a particular user; several timings are needed for a good estimate. However, we believe that it may be possible to group several digrams together, and thus group several single points into a distribution, to compare against the profile's digram groups. The question is whether there are digrams or durations that are sufficiently similar in order for them to be grouped together without losing accuracy. We have found that many digrams and durations share the same average and standard deviation of timing, but we have not looked at the complete distributions of timings for different digrams or durations from the same user. If the distributions match as closely as the average and standard deviations do, then it would be possible to group the digrams or durations, and thus have more data points within each grouping to do calculations with. Because each user has a unique pattern for their durations and digrams, the groups would need to be specific to each user. The result of this would be that we would be able to reduce the number of keystrokes needed to accurately determine a user's identity.

1. Gaines, R., W. Lisowski, S. Press, and N. Shapiro. "Authentication by keystroke timing: some preliminary results." Rand Report R-256-NSF (1980).

2. Leggett, J. and G. Williams. "Verifying identity via keystroke characteristics." International Journal of Man-Machine Studies (1988): 67–76.

3. Joyce, R. and G. Gupta. "Identity authorization based on keystroke latencies." Communications of the ACM (February 1990): 168–176.

4. Monrose, F. and A. Rubin. "Authentication via keystroke dynamics." In Proceedings of the 4th ACM Conference on Computer and Communications Security (April 1997): 48–56.

5. Bergadano, F., D. Gunetti, and C. Picardi. "User authentication through keystroke dynamics." ACM Transactions on Information and System Secu-rity 5(4) (Nov 2002).

In the spring of 2004, the Keyboard Biometrics team emerged out of CSC200: Undergraduate Research Seminar. Consisting of two sophomores (Lu and Ganzhorn)and three seniors (Ordal, Norwood and Fong), the group was advised by Professor Michael L. Scott. Ordal is currently working for UR Admissions. Norwood is employed by Gestalt LLC. Fong is training to be a Radiation Treatment Dosimetrist at Memorial Sloan Kettering Cancer Center. Both Ganzhorn and Lu are currently working on their honors senior thesis, in Simulation of Societal Evolution, and the Automatic Transcription of Music using Genetic Algorithms and MIDI synthesis, respectively.

Violin Acoustic Radiation Synthesis:

A Source Model for Direct Sound Enhancement in Musical Acoustic Environments

Jacob Waxman, 2005

Department of Mechanical Engineering

Advised by Mark Bocko, Ph.D.

Reproducing sound in a listening space where all of the sound sources are correctly modeled in 3-dimensions and then projected via speaker to generate a desired listening experience, known as an immersive acoustic environment, has been an interest of acousticians, musicians and listeners alike for many years. Within the context of "musical telepresence,"–rendering musical sound and its associated spatial acoustic properties in a given room remotely via Internet-2 (commercially unavailable lines which have a larger bandwidth and less signal delay) for the purpose of real-time interactive musical performance--there are many factors that determine the nature of this musical experience. Of particular interest are the spatial properties of the radiated sound field emanating from a bowed violin whose far-field directivity patterns vary rapidly as a function of the fundamental frequency corresponding to the various notes played within the 1 – 5 kHz range.[1] We can identify an instrument "that sounds like a violin" without any spatial information. For example, spatial information may tell us where it is located in space or in which direction(s) the instrument prefers to send acoustic energy, as prescribed by the instrument's physics. But it is spatial information which may determine how we experience sound in an immersive acoustic environment.

Scenario

With the goal of transmitting audio data (both the music and the spatial properties of the sound radiating from musical instruments) in real-time between two locations via Internet-2 (see Fig 1.2.1), all of the perceptually relevant information must be encoded properly. In order to circumvent the problems associated with processing, encoding, and transmitting multi-channel audio data via Internet-2, the directivity patterns are modeled using a multipole expansion (in the form of a cylindrical harmonic decomposition) as a function of frequency. The expansion coefficients are then stored in a dedicated processor at the speaker output destination which are indexed according to their multipole order and the fundamental frequencies of the notes played on the violin; coefficients can then be interpolated for notes whose fundamental frequencies lie between those whose multipole weights are calculated. With the proposed configuration in Fig. 1.2.1, the only data needed to be sent is the violin orientation (in this particular case the front and back plates are considered to be parallel to the floor) and the sound radiated from the violin which is recorded by one microphone. In addition to the expansion coefficients, the location of the microphone relative to the violin in "Room 1" within the azimuthal plane is stored in the processor such that the amplitude of the recorded signal can be normalized accordingly. With this information, a horizontal sound imaging processor can calculate the correct driving signals for the speaker array (a circular array in this case) in the second room, such that the wave front (i.e. the directivity pattern) of the real violin can be reproduced in the form of a virtual source as predicted by Huygens' principle for the outgoing waves.[2] A flowchart (Fig. 1.2.2) of the operations required to generate a synthesized version of the wave field is below.

Violin Directivity Measurements and Synthesis

Violin excitation and directivity measurements

A bowing machine was constructed by Wang for the purpose of exciting the violin over a range of pitches whose fundamental frequencies exist between 100 Hz and 5000 Hz. While exciting these pitches, an omnidirectional microphone circled around the violin on a boom at a radius of 2 m from its center (and thus in the far-field), and measured a 1.56 Hz narrow band spectrum in 5° increments from which the directivity patterns were generated.[3] From these measurements, it is clear that the overall shape of the directivity patterns change drastically in the 1 – 5 kHz range when the note played only differs by a semitone. Furthermore, as fundamental playing frequency increases the directivity patterns become increasingly complex with many nulls and lobes varying as a function of angle around the violin. It should be noted that the radiation patterns vary minimally when the same note is played on different strings. This is a very important observation within the context of reproducing the radiation patterns over Internet-2: since the directivity patterns can be modeled independent of the string being played, the amount of data needed to be encoded and transferred is reduced by excluding string dependency as a potential parameter.

Theory and Methodology for Synthesis

A feasible approach for modeling the far-field directivity patterns of the violin is by way of a multipole expansion. This

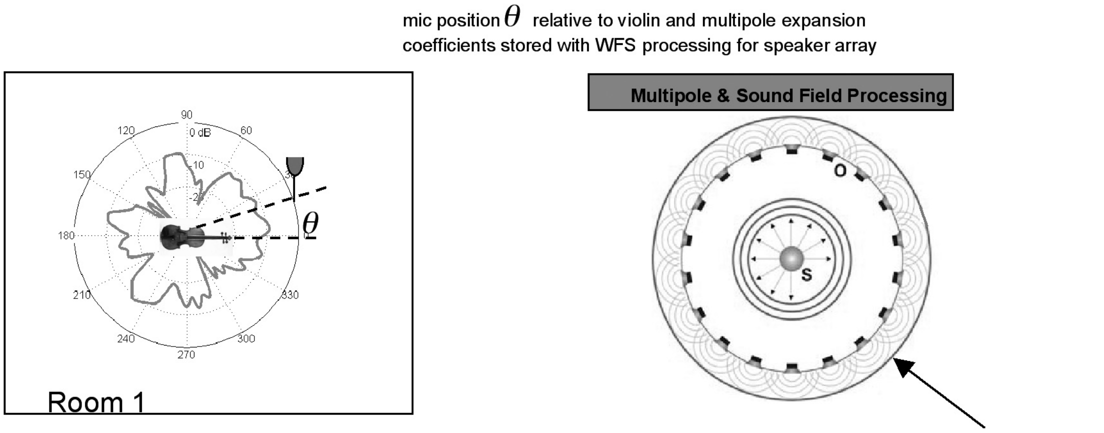


Fig. 1.2.1: A representation of audio data transmission (both the music and the spatial properties of the sound radiating from musical instruments) in real-time between two locations via Internet-2.

scenario resembles that of an exterior domain problem,[4] with the radiating violin body located at the center of the circle with a 2 m radius whose boundary is prescribed by the microphone array. Since the far-field microphone pressure measurements used here only correspond to the azimuthal plane, a cylindrical harmonic decomposition is used. This plane is of particular importance due to the fact that the listener's ears lay in this plane of direct sound propagation.

In order to extract the expansion coefficients for varying multipole order, the angular and radial dependence must be accounted for. Firstly, the angular dependence of the sound field must be removed using a circular Fourier transform:

$$P(k_\theta,\omega)=\frac{1}{2\pi}\int_0^{2\pi} p(\theta,\omega)e^{-jk_\theta\theta}d\theta \qquad (1)$$

where p corresponds to the microphone pressure measurement at angular position θ and frequency ω, and P corresponds to the angular spectrum as a function of multipole order k_θ and frequency.[5] In order to extract the multipole coefficients from P, we must remove the radial dependence pertaining to the outgoing waves:

$$M^{(2)}(k_\theta,\omega)=\frac{P(k_\theta,\omega)}{H_{k_\theta}^{(2)}(kR)} \qquad (2)$$

where $M^{(2)}$ corresponds to the desired coefficients of varying multipole order, and $H_{k_\theta}^{(2)}$ corresponds to the Hankel function (Blackstock, 2000 for an explanation of Hankel functions) with k equaling the wave number and R equaling a radius of 2 meters (the superscript "2" refers to outgoing waves as opposed to incoming).[6] The synthesis equation is as follows:

$$p(r,\theta,\omega)=\sum_{k_\theta} M^{(2)}(k_\theta,\omega)e^{jn\theta}H_{k_\theta}^{(2)}(kr) \qquad (3)$$

Although the synthesized pressure values can be calculated at any distance r from the violin, the distance of $r = R = 2$ meters is the value used for synthesizing the directivity patterns here.

Matlab Synthesis, Results and Analysis

In the technical computing platform of Matlab, equation (1) was modified in the form of a Discrete Fourier Transform, given that the pressure measurements were spaced evenly in 5 degree increments along a circle and additional values were interpolated between measurements in order to generate a vector of 360 points. After extracting the multipole expansion coefficients using equation (2) the directivity patterns were synthesized up to 8th, 16th, and 32nd order multipole reconstruction for the purpose of comparison. Measured directivity patterns (Fig. 1.2.1 for violin orientation with respect to directivity pattern) along with their synthesized versions (red line = measured directivity and blue line = synthesized directivity) are shown in Figs. 2.3.1-2.3.3 for various notes whose fundamental frequency corresponds to the frequency listed in the caption:

From Fig. 2.3.1 it is evident that the spatial harmonics present in the measured pattern require only a few multipole orders for accurate reconstruction. However, Figures 2.3.2 and Figures 2.3.3 suggest that as the fundamental frequency of the note played increases we find the radiation patterns to be very complex, with many large nulls and lobes, thus requiring higher multipole orders for reconstruction. Figure 2.3.4 hints at a possible psychoacoustic consequence of rendering an acoustic field without accounting for high spatial harmonics (the listener's head is assumed to be located approximately 10 ft from the source and thus subtending an angle of approximately 6 degrees). Synthesizing a sound field with incorrect values of the acoustic pressure at each of the listener's ears will most likely affect the listener's ability to localize the sound (for explanations of "inter-aural level difference", i.e. the magnitude difference between the signals in each ear, see Blauert, 1997) and/or affect their perception of directional tone color.[7]

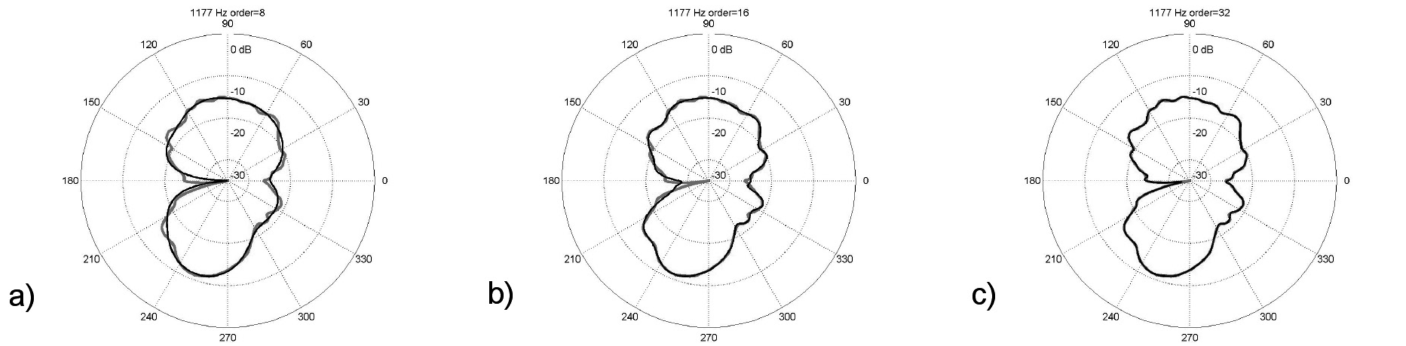


Fig. 2.3.1 The measured (thick line) and synthesized (thin line) directivity patterns at 1177 Hz, for a) 8th order b) 16th order c) 32nd order reconstruction.

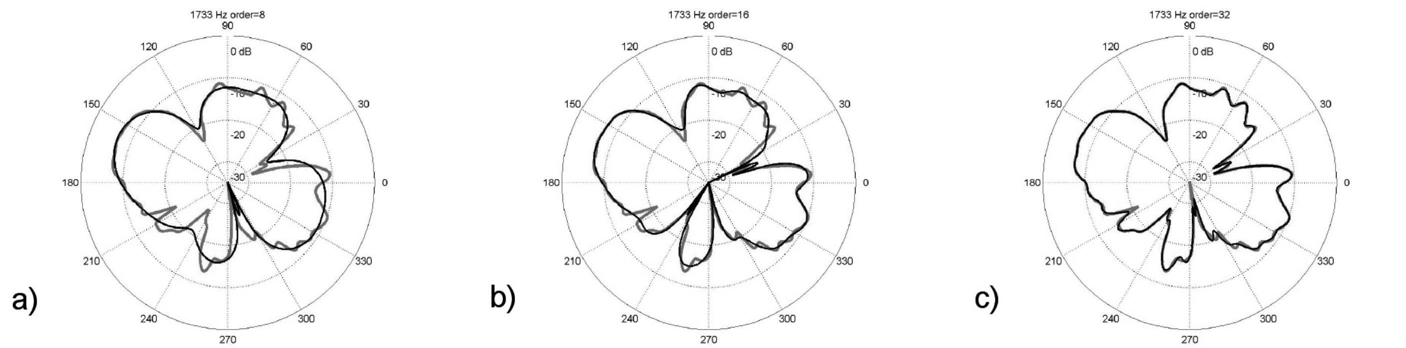


Fig. 2.3.2 The measured (thick line) and synthesized (thin line) directivity patterns at 1733 Hz, for a) 8th order b) 16th order c) 32nd order reconstruction.

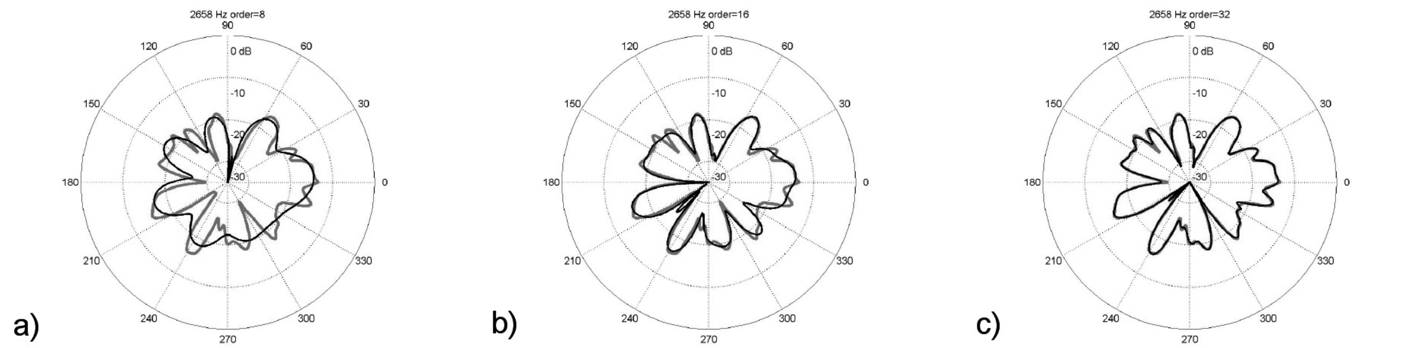


Fig. 2.3.3 The measured (thick line) and synthesized (thin line) directivity patterns at 2658 Hz, for a) 8th order b) 16th order c) 32nd order reconstruction.

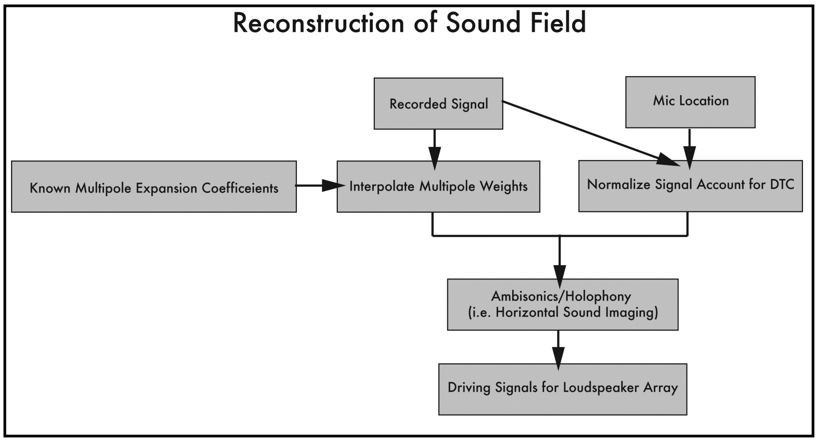


Fig. 1.2.2: A simplified flowchart of the operations required to generate a synthesized version of the wave field.

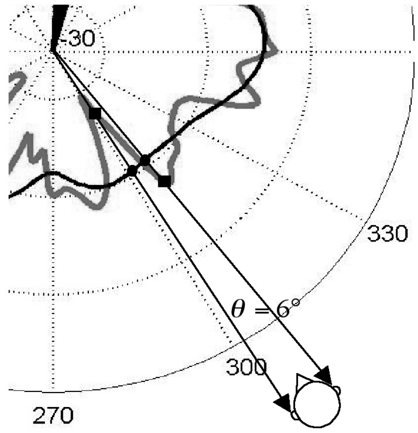


Fig. 2.3.4 The magnitude values of the sound field in each ear for the synthesized pattern (circles) and measured pattern (squares) with the head subtending a 6 degree angle with respect to the source. (This is a magnified area of Fig 2.3.3.a)

In the case of a cylindrical harmonic decomposition is important to note that the number of loudspeakers required to reproduce a field of order k_θ equals $(2k_\theta + 1)$, thus bearing a strong resemblance to High Order Ambisonics (HOA).[8] In this instance however, the speaker array is pointing outward, thus providing the counterpart to HOA (Daniel, 2003 mentions that HOA assumes a "centered point view" and therefore prescribing the listening area to be inside the circular array in a "surround sound" type setup as opposed to the configuration proposed here) which can also be realized in the form of Wave Field Synthesis (WFS). Although originally thought of as two different methods of sound reproduction, we find that both HOA and WFS are in fact equivalent since they can both be derived from the Kirchoff-Helmholtz integral which describes the physical phenomena illustrated by Huygens' principle.[9]

Conclusions and Further Research

Clearly, listening tests must be performed in order to gain a more comprehensive understanding of the perceptual effects associated with synthesizing a violin's directivity pattern. A feasible test might be to systematically vary the multipole reconstruction order as a means of pinpointing the human tolerance for error. The results of the listening tests may be a function not only of angle but also of distance from the perceived source. Furthermore, the data used to model the directivity patterns only give us an understanding of these patterns at steady state, and not the change in directivity between notes, which may greatly affect our perception of the instrument's spatial acoustic properties.

Acknowledgements

I would like to thank Professor Lily M. Wang at the University of Nebraska – Lincoln, for her great generosity in lending me her data in order to pursue this research, as well as Professor Mark Bocko of the Electrical and Computer Engineering Department at the University of Rochester for being a great mentor to me during the course of my undergraduate education.

1. Weinreich, G. "Directional Tone Color." J. Acoust. Soc. Am. 101 (1997): 2338-2436.

2. Berkhout, A.J., D. de Vries, and P. Vogel. "Acoustic Control by Wave Field Synthesis." J. Acoust. Soc. Am. 93 (2000): 2764-2778.

3. Wang, L.M. "Radiation Mechanisms from Bowed Violins." Diss., thesis, Pennsylvania State University, 1999.

4. Williams, E.G. Fourier Acoustics. New York: Academic Press, 1999.

5. Hulesebos, E., D. de Vries, and E. Bourdillat. "Improved Microphone Array Configurations for Auralization of Sound Fields by Wave-Field Synthesis." JAES 50 (2002): 779-790.

6. Blackstock, D.T. Fundamentals of Physical Acoustics. New York: Wiley-Interscience, 2000.

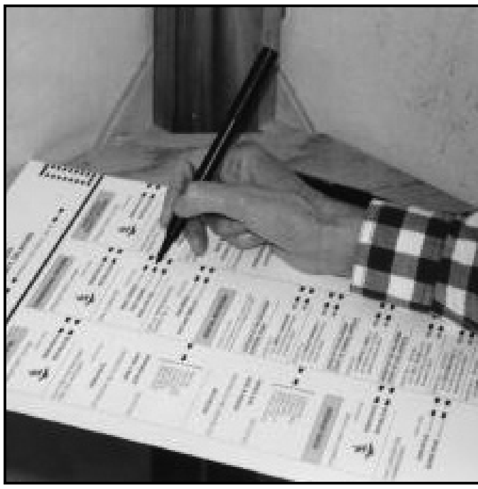
7. Blauert, J. Spatial Hearing. Boston: MIT Press, 1997.

8. Daniel, J., R. Nicol and S, Moreau. "Further Investigations of High Order Ambisonics and Wave Field Synthesis for Holophonic Sound Imaging." Proceedings of the AES 114th Convention (2003).

9. Nicol, R. and M. Emerit. "3D-Sound Reproduction over an Extensive Listening Area: A Hybrid Method Derived from Holophony and Ambisonic." Proceedings of the AES 16th International Conference. (1999): 436-453.

Jacob (Cobi) Waxman '05, a Mechanical Engineering major and Electrical Engineering minor, presented this research at a special session on the "Integration of Synthesis Techniques and 'Acoustic' Music" at the 148th meeting of the Acoustical Society of America in San Diego in November 2004. As a musician, ethnomusicologist and scientist, Cobi will continue to explore the nature of musical sound and its relevance within the context of human life.

Strength of Political Views in Young People and their Parents: A Questionnaire Study



Laura Maruskin, 2006

Advised by Kirk Warren Brown, Ph.D.

Clinical and Social Sciences in Psychology

A questionnaire study was conducted to investigate the relationship between the strength of the political views of young people and those of their parents. Subjects consisted of 74 University of Rochester undergraduates who completed questionnaires that focused on their political views and their perceptions of their parents' political views. The questionnaires, designed to evaluate the strength of political views, used 5-point Likert scales to rate the frequency of participation in certain political issues and the importance of political issues in one's life. Corresponding questions between young people and their parents were correlated. Overall, results showed positive and significant correlations between the strength of a young person's political views and that of their parents. That is, the results showed that the stronger the political views of a young person, the stronger the political views of his or her parents.

The 2004 presidential election has drawn much attention to the voting habits of Americans, especially those of young people. Interest seems to have been sparked by the fact that an overwhelming proportion of young Americans (18-24 year olds) that are eligible to vote choose not to do so, and further more, the proportion of those that don't vote is increasing.[1] In a country that prides itself on its system of democracy, this fact is perplexing, even disturbing. So, the question that undoubtedly comes to mind is: *why not?* Further, what factors influence whether one votes or not? Many possibilities have been considered in past research. The present study extended existing research and investigated the potential influence of the strength of a young person's parents' political views on the strength of his or her views.

As mentioned above, the issue of individuals' voting habits has been examined from myriad angles. For instance, Feld explored the relationship between individuals' specific political attitudes and their personality.[2] He found that various relations existed between these variables, suggesting that personality has a potential influence on voting habits. In another study, Breakwell, Fife-Schaw, and Devereux considered teenagers' specific political attitudes in relation to their political activity.[3] They found that individuals holding left-of-center political views were more politically active than others. Further, these individuals reported paying more attention to political television shows and newspaper articles, as well as having more political discussions with teachers and parents. In 2004, Richardson more directly examined the relationship between participation in political discussions and political activity in young people.[4] Using survey data, he found that young people who reported more frequent discussions of politics with others (including peers, parents, and teachers) were more likely to be engaged in civic activities at the present time, and in addition, were more likely to believe that they would engage in civic activities in the future, as adults. Thus, the findings supported the notion that increased political discussion may positively influence political activity.

Different aspects of individuals' environments have also been explored as potential influences on voting habits. From a broad perspective, a few studies have examined the potential influence of the media on voting habits.[5,6] Johansson found a correlation between the degree of exposure to the mass media and young people's political knowledge and values.[5] This lends support to the notion that this element of a young person's environment can influence voting habits. Community has also been considered as a potential environmental influence on voting habits. Knack and Kropf found that the probability that a person will vote increases as the cooperative norms in his or her community increases.[7] Cooperative norms in a community were evaluated in a variety of ways, including census response rates, giving to charities, and willingness to serve on juries.

Finally, a few studies have begun to consider potential parental influences on voting habits. Koenig investigated the relationship between college students' preferences for candidates and their parents' preferences for candidates in two presidential elections (1972 and 1976).[8] It was assumed that students who favored Republican candidates would be more conservative than students who favored Democratic candidates. Therefore, the researcher hypothesized, students who favored Republican candidates would perceive their parents as having the same views as themselves more than students who favored Democratic candidates. This hypothesis was supported by the data from both presidential elections that were studied. In another study related to parental influence on voting habits, Westholm explored the transfer of political values across generations, from parent to child.[9] The transfer itself was viewed as a two-step process. The first step was characterized by the child's perception of the parent's views, and the second by the persuasion for the child to have the same views. The researcher evaluated the prevalence of each of these steps in the transfer of values against each other. The results indicated that the step characterized by the child's perception of his or her parent's political views was more important in the transfer of views.

With this work as background, the present study focused on the parental influence on the voting habits of young people, and extended the existing research. In an attempt to investigate the factors that influence whether young, educated people choose to vote, the strength of the political views of college students and their perception of the strength their parents' views were evaluated. It was hypothesized that the greater the young person's perception of the strength of his or her parents' political views, the greater the strength of his or her own political views. The practical implications of this study are significant in that by gaining insight into the factors that influence the voting habits of young people, steps can be made to more effectively encourage young people to vote.

Method

Participants

The study was conducted at the University of Rochester using undergraduate students from a voluntary subject pool. Students signed up for the study as part of a variety of questionnaires using the online Sona Psychology Research Participation System. A total of 74 students signed up for the study and 74 students completed the study to form the sample. The participants included 23 males and 51 females. The age of participants ranged from 18 to 23 years, with a mean of 19.667 and a standard deviation of 1.239. Compensation was given to the participants in the form of 1.5 chits of extra credit towards their psychology courses.

Measures and Procedures

The questionnaires used were designed to evaluate the strength of the participant's political views and the perception of those of his/her parents for the sake of comparison. The first portion of the questionnaire, titled "Political Scale," aimed at evaluating the strength of the participant's views. It was developed by the researcher and included 8 questions scaled on 5-point Likert scales. Political views were evaluated explicitly, by simply asking the participant to rate the importance of politics in his/her life. Political views were also evaluated implicitly, focusing on such relevant issues as the participant's frequency of participating in political discussions, exposure to political issues through various forms of media, and involvement in political activities. An example of a question in this section of the questionnaire is: "How frequently do you discuss politics with friends or family?" The second portion, titled "Political Perception Scale," focused on the participant's perception of the strength of his/her parents' political views, collectively. It was also developed by the researcher and included 8 questions scaled on 5-point Likert scales. The questions were in the same form as those in the first section, both explicit and implicit, but asked the participant to evaluate his/her parents' views. An example of a question in this section is: "How often do your parents discuss politics with friends or family?" Finally, the third section of the questionnaire, titled "Further Questions," included questions with a more demographic nature, such as whether the participant/parents were registered to vote, and whether they planned to vote in the upcoming election. All questions were closed-ended. Answers to questions in the first and second sections were scaled using 5-point Likert scales, ranging from 1 (not at all frequently) to 5 (very frequently) for frequency questions and 1 (Not at all important) to 5 (very important) for explicit questions. The third section included questions with multiple choice answers as options.

Participants completed the questionnaires in a large classroom with pencil on scantron sheets, as a part of the larger packet of questionnaires. Participants entered the room and the questionnaire packets, scantron sheets and pencils were passed out to them. Participants were given an hour and a half to complete the entire packet of questionnaires.

Table 1. Mean Scores and Standard Deviations

	Subject			
	Young person		Parent	
Question	Mean	SD	Mean	SD
Discussing politics with friends/family	2.70	1.144	2.82	1.175
Reading newspaper articles related to politics	2.09	1.161	3.43	1.228
reading magazine articles related to politics	2.04	1.039	2.84	1.205
reading books related to politics	1.45	0.779	2.03	1.146
Watching TV related to politics	2.84	1.073	3.85	0.989
Thinking about political issues on own	2.78	1.185	3.31	1.084
Participating in political demonstrations	1.26	0.525	1.36	0.786
Level of importance of the role of politics in one's life	2.54	1.023	3.3	1.003

Results

Individual items on the young person's political view scale and the perception of the parents' political view scale were compared. Pearson product correlations were used to correlate corresponding items between the questionnaires that focused on the political views of the young person and those of their parents. Tables 1 and 2 summarize the findings. The frequency with which young people discuss politics with friends or family is significantly positively correlated with the frequency with which their parents discuss politics with friends or family ($r(72)=.491$, $p<.01$). Thus, the higher the frequency with which young people discuss politics with friends or family, the higher the frequency with which their parents do so. The frequency with which young people read newspaper articles related to politics, however, is not significantly correlated to the frequency with which their parents do so ($r(72)=.038$, $p>.01$) . The frequency with which young people read magazine articles related to politics is significantly positively correlated with the frequency with which their parents read magazine articles related to politics ($r(72)=.301$, $p<.01$). The higher the frequency with which young people read magazine articles related to politics, the higher the frequency with which their parents do so. The frequency with which young people read books related to politics is not significantly correlated with the frequency with which their parents do so ($r(72)=.216$, $p>.01$). However, the frequency with which young people watch television reports related to politics, think about political issues or their own, and participate in political demonstrations are all positively significantly correlated with the frequency with which their parents watch television reports related to politics,think about political issues on their own, and participate in political demonstrations ($r(72)=.287$, $p<.05$, $r(72)=.330$, $p<.01$, $r(72)=.301$, $p<.01$ (respectively)). So, the higher the frequency with which young people watch television reports related to politics, think about political issues on their own, and participate in political demonstrations, the higher the frequency with which their parents do so. Finally, the level of importance of the role that politics plays in a young person's life is significantly positively correlated with the perceived level of importance of the role that politics plays in their parents' life ($r(72)=.629$, $p<.01$) .

To examine the influence of each component included in the questionnaire of the parents' political views on the self-reported importance that politics play in a young person's life, a simple regression was used. The dependent variable was how important the young person rated the role of politics in his or her life. The set of predictors was the set of answers to the questions about the young person's parents' political activities on the "Political Scale." The regression yielded a significant R of .467, $F(7, 73)=2$, and the only significant predictor was the frequency with which parents discussed politics with friends of family (beta=.376, $t(73)=2.154$, $p<.05$).

Discussion

Overall, the results supported the hypothesis that the greater a young person's perception of the strength of his or her parents' political views, the greater the strength of his or her *own* political views. All correlations between corresponding items on the young person's political questionnaire and his or her parents' political questionnaire were positive and significant, with the exception of two items. These positive, significant correlations show that the higher the frequency with which a young person participates in activities related to politics and the more important a role politics plays in a young person's life, the higher the frequency with which his or her parents participate in activities related to politics and the more important a role politics plays in his or her parents' lives. The two items that were exceptions to this were the frequency with which one read newspaper articles related to politics and the frequency with which one read books related to politics. The correlations for these items between the young person and parents were positive, but not significant. This can be explained by considering restriction in the range. Each of these behaviors tend to occur relatively infrequently among subjects, so it makes sense for the data for these variables to be clustered in the lower portion of the range. Thus, there is a positive correlation, but it is not significant because each variable correlated covers such a small portion of the range. Also, a regression analysis showed that the frequency with which parents discussed politics with friends or family was the only significant predictor of how important the young person rated the role of politics in his or her life. This seems to be likely, since this item was the only one that involved direct interaction between the parent and child. So, it seems logical that high frequency of discussing politics in the parents predicted a higher level of importance of the role of politics in a young person's life.

The findings extend the research of Westholm, which suggested the importance of a child's perception of his or

Question	Correlation coefficients
Discussing politics with family/friends	0.491*
Reading newspaper articles related to politics	0.038
Reading magazine articles related to politics	0.301*
Reading books related to politics	0.216
Watching TV reports related to politics	0.287**
Thinking about politics issues on own	0.330*
Participating in political demonstration	0.301**
Level of importance of the role of politics in one's life	0.629*

Table 2. Correlation coefficients between young person's political view scale and the parents' political view scale on corresponding questions where n=74.
* $p < 0.01$, ** $p < 0.05$

her parents' political views.[9] Westholm studied the transfer of specific political views across generations and found that a child's perception of his or her parents' views was more significant in the transfer than persuasion for the child to have the same views. In the present study, the strength of political views were studied and compared between generations, with focus on the perception of political views. Thus, the two studies are similar in their consideration of the perception of political views, but different in that the past study focused on specific political views while the present study focused on the strength of political views in general. Further, the findings are consistent with the broad Social Learning Theory, which stresses the importance of environmental factors on the development of one's views. The present study reinforced the notion that parents, as an element of the environment to which young people are exposed, may be an important factor in the development of a young person's political views.

While the study was successful overall, various improvements could certainly be made. The main flaw in this study seems to be the lack of external validity as a result of the very limited sample. The sample was quite small and was made up entirely of educated, relatively wealthy, college students. Thus, it seems highly unlikely that a sample with these characteristics would be representative of the population as a whole. The task of formulating a representative sample is by no means an easy one, but it does not seem like it would be too hard to improve on the sample used in this study. Another problem with the study is that of the range in the three items mentioned above. This, however, could be fixed quite easily by adjusting the scales that were used to measure them. This way the variables could be evaluated more precisely. Finally, significant improvement would be made if the items on each of the questionnaires were combined to form a reliable scale. This way, further statistical analyses could be performed and more comprehensive conclusions could be drawn. Thus, a possibility for new research would be a study designed to validate scales formed by these questionnaires. Once a scale is established, it can be applied to different populations to assess the strength of their political views and then comparisons can be made between these populations. For example, one could compare the strength of the political views between siblings and see how they are correlated. This would allow further insight into voting habits of young people.

By exploring the factors that influence the strength of young people's political views, this study provides insight into the voting habits of young people. The study offers further evidence for the relationship between the political views of young people and those of their parents, specifically concerning the strength of political views. Its theoretical implications are both particular and universal. On a particular level, the study extends past research on the transfer of political views between generations and on a universal level, it reinforces key elements of the Social Learning Theory. The study has considerable practical implications as well. Given the insight it provides into the relationship between the strength of the political views of young people and their perception of the strength of their parents' views, the factors that contribute to strong political views in young people can be further understood. By working to increase these factors, it may be possible to increase the likelihood that young people choose to vote. Thus, this study can be seen as an advance in the effort to get young people to vote in presidential elections.

---

1. Levine, P. & Lopez, M. H. Youth voter turnout has declined, by any measure. Retrieved September 21, 2004, from http://www.civicyouth.org/research/products/fact_sheets_outside.htm. 2002.

2. Feld, P. J. "A prospective longitudinal study of personality and political orientation." Dissertation Abstracts International: Section B: The Sciences and Engineering (1995): 56, 2921.

3. Breakwell, G. M., Fife-Shaw, C., & Devereux, J. "Political activity and political attitudes in teenagers: Is there any correspondence? A research note." Political Psychology 10 (1989): 745-755.

4. Richardson, W. K. "Connecting political discussion to civic engagement: The role of civic knowledge, efficacy and context for adolescents. An Exploratory Study." Dissertation Abstracts International Section A: Humanities & Social Sciences (2004): 64, 3193.

5. Johansson, O. "Youth and mass media: On the covariation between mass media use and democratic values." Politics and the Individual (1991): 1, 49-65.

6. Speckman, K. R. "American voters' use of community and the media in determining whether to vote: An Exploratory Study." Dissertation Abstracts International Section A: Humanities & Social Sciences (2004): 54, 3249.

7. Knack, S., & Kropf, M. E. "For Shame! The effect of community cooperative context on the probability of voting." Political Psychology (1998): 19, 585-599.

8. Koenig, F. "Preferences for candidates of college students and their parents in two presidential elections." Psychological Reports (1982): 50, 335-336.

9. Westholm, A. "The perceptual pathway: Tracing the mechanisms of political value transfer across generations." Political Psychology (1999): 20, 525-551.

Laura Maruskin is a senior double majoring in Psychology and Philosophy at the Universtity of Rochester. Her future plans include studying Psychology at the graduate level and continuing research in the field. She became interested in performing research by working as a research assitant in motivational psychology. Laura feels it is important to expand the body of research in the psychological discipline and is looking forward to contributiong to that process.

Accretion Region Variability Mechanisms in Low Luminosity AGN

Grant Tremblay, 2006

Advised by Alice C. Quillen, Ph.D.

Department of Physics and Astronomy

Some low luminosity hosts of active galactic nuclei (AGN) are known to boast short variability timescales, allowing practical quantitative analysis of the outer accretion region (a region at the very center of the AGN in which matter falls inward toward a black hole, liberating large amounts of energy). Specifically, observationally deriving wavelength-specific time lags via line reverberation mapping gives us clues as to the structure of the accretion region and allows us to constrain the mass of the central black hole (BH). Regardless, the processes driving brightness variability in AGN are difficult to describe quantitatively, and in the case of some low luminosity AGN (LLAGN), we find that rapid, dynamic physical processes must occur within the accretion region so as to drive the high amplitude, high frequency variability that is observed. Here we present a qualitative survey of several theoretical accretion region variability models, highlighted by experimental data and an observationally supported discussion of the quality of such models. In doing so, we hope to motivate a coupling between the known physical properties of LLAGN and the unification paradigm for generalized AGN, so that we may begin to quantitatively strengthen accretion region models for both.

The widely accepted unification paradigm of active galactic nuclei holds that the ultra-luminous cores of AGN host galaxies are powered by accretion onto a central supermassive black hole. In many cases, AGN exhibit intrinsic, sometimes highly aperiodic variability in continuum profiles, a property suggestive of a kinematically hot, dynamic accretion region. By "continuum variability", we mean variations in AGN brightness over a period of time, (somewhat analogous to a flickering light bulb). Such variability is seen as the emission spectrum (continuum) of an AGN, especially when comparing two spectra of one object taken at different times (see Fig. 2 for a dramatic example). Unfortunately, studies of variability mechanisms in these active regions must be conducted indirectly, as the size scales for inner accretion environments are on the order of a few parsecs, mapping only to microarcsecond scales on the sky for AGN at high redshift (Z > 0.5, conservatively), where the majority are found (this makes sense, because AGN are widely regarded as young systems, so we expect them to be farther away). Despite these difficulties, spectral analysis yields several predominant, nearly universal features of the AGN accretion region, which while supportive of the unification paradigm, are not well understood.

In this paper we will discuss several predominant, theoretically generated models for driving AGN variability, which can often be quite rapid and dramatic. The majority of these models are constrained to the accretion region, extending to a radius of only a parsec, and so we must first discuss the structure of the AGN in terms of observationally derived findings, as well as the theoretical timescales of the region. We do this because, if AGN are observed to vary by orders of magnitude so rapidly (which they are, sometimes on the order of several days), then constraining physically based timescales in this region will provide a test for any theoretical model we present. Any violation of these timescales will suggest that the model being discussed may be physically unreasonable.

We then focus our discussion on the scientific value of extreme cases of AGN, specifically NGC 4395, the nearest and lowest luminosity Seyfert (AGN host galaxy) known. More importantly, NGC 4395 has been observed to vary in brightness by nearly 25% in only four days. Such properties make studies of this object not only practical, but rewarding as well. For, while extreme in both luminosity and variance, NGC 4395 still has a place within the unified model of AGN, and so it is reasonable to assume that its variability is powered by the same processes present in more common, less dramatic specimens. In exploring the properties of extreme objects, we learn more about the generalized model of AGN accretion regions, and the theory becomes all the more robust.

Observations and Theory

In this section, we will discuss in detail the unified model for AGN accretion region structure. Emission line studies reveal that, in many cases, AGN spectra reveal a heavy optical/ultraviolet (UV) component with a double-peaked Balmer line profile, suggesting a gaseous, optically thick Keplerian disk is present in the region surrounding the black hole. Also observed is a pseudo-spherically distributed, hard X-Ray emitting component overlapping the inner edge of the cool, UV disk. These components will be discussed individually in Narrow- and Broad-Line Region Properties sections, respectively, followed by a brief description on current research in coupling the two with a continuous, self consistent model, namely by

Czerny, Rózanska & Kuraszkiewicz (2004). This discussion is necessary because if any physical variability mechanisms intrinsic to AGN are to exist, then they can only reasonably do so in this region. A better understanding of this structure leads to a better understanding of processes occurring within it.

Narrow-Line Region Properties

Broad band spectra of Seyfert cores reveal heavy AGN contribution to short-optical/UV wavelengths. Because of its nearly universal appearance in AGN spectral energy distributions (SEDs), it has been coined the "big blue bump" (BBB), a spectral feature which can extend into soft X-Rays in some Seyfert specimens.[1] Also notable is the presence of a Balmer edge, seen near ~4000 angstroms in Fig. 1. This strongly suggests that the continuum source is made up of a gaseous, optically thick material. Furthermore, there is strong, albeit circumstantial evidence that this gaseous component roughly assumes the form of a Keplerian disk. This argument is supported by the existence of a small sub-class of AGN whose spectra contain double-peaked emission lines, a feature produced by a spatially thin, optically thick gaseous disk.[2] (As stellar matter spirals inward towards a BH, it settles into a thin accretion disk so as to conserve angular momentum). Also evidence of disk-like structure is the fact that similar features appear in soft X-Ray novae.[1] The most dramatic evidence for an accretion disk, however, is the presence of polar jets in AGN, always perpendicular to the plane of the galactic disk. These jets must be produced by gravitational scattering off the black hole, and their "polar" structure suggests that they originate from an axisymmetric accretion disk, also lying within the galactic plane. These jets are the mechanisms by which excess angular momentum from the accretion disk is carried away from the black hole, (because the angular velocity of the BH cannot exceed the speed of light). The BBB region of AGN spectra is produced by the inner edge of the disk (which makes sense, as we expect relatively hot material to be radiating in the UV). As thermal excitement increases as an inverse function of radius from the BH, we expect gradual cooling of the accretion disk at further distances, so much so that infrared (IR) emission becomes prominent at the disk's outer edge. IR observations of AGN reveal this to be the case. Furthermore, constraints on the radius of the accretion disk can be derived via line reverberation mapping, in which arrival time lags observed in UV/IR comparisons are coupled with reprocessing timescales for optical/UV light absorbed at the inner edge of the accretion disk and thermally reradiated in the infrared at the opposite end. For a more detailed description of this numerical process, we refer you to work by Brad Peterson, namely Peterson & Horne (2004). The outer accretion disk and a surrounding molecular halo make up the narrow-line region (NLR) of the AGN, named so for the low velocity dispersions of its constituent particles (e.g. the effect of Doppler broadening in emission lines from this region is very small). This is in contrast to the counterpart of the NLR, the broad-line region (BLR), which will be discussed in the following section.

Broad-Line Region Properties

Observationally, the broad-line region, a small, spherical volume of space immediately surrounding the black hole, seems like a disjoint superimposition over the spectra of

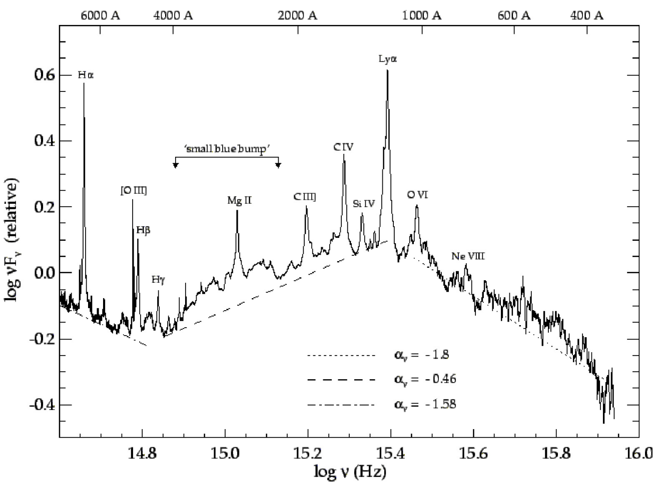


Figure 1. Optical/UV composite AGN spectrum. Note the "big blue bump" centered about log _ = ~15.3 Hz (~1300Å). The bracketed area of the spectrum highlights the presence of a double peaked Balmer line profile (~4000Å), suggesting the emitting material has a disk-like structure.[9]

the cold accretion disk. Being an optically thin, hard X-Ray emitting area, it is most likely made up of superheated plasma. Quantitatively, possible constraints on the "radius" (we use the term loosely, as there is no definite boundary to the BLR) might be made by coupling estimates based on Eddington luminosity ratios with geometries of stable orbits within the disk. Specifically,

$$R_{\rm BLR} \propto \zeta \left(\frac{\lambda L_{\lambda}(5100)\mathring{A}}{10^{44}}\right)^{\mu} \quad (1)$$

where ς, of order unity, is ~30, and μ, also of order unity, is around 0.7, as proposed by Czerny et al. (2004).

Observations also reveal that, in some Seyfert specimens, broad line emission can be reflected or polarized, suggesting that many unique features of observed BLR spectra may in fact be artifacts of orientation angle.[4,5] Since the torus of an accretion disk lies in the plane of the galaxy, it is reasonable to assume that extinction will play a large role in BLR observations.

Despite the apparent dichotomy between their two spectra, there must be some physical connection between the cold accretion disk and the hot plasma, as inward falling matter must feed the coronal BLR from the torus. The structure of the BLR is the dividing factor, however, so any model attempting to bridge the gap between the two regions must provide an adequate explanation for the spheroidal distribution of the hard X-Ray emitting material.

We refer the reader to Czerny et al. (2004), in which the authors attempt to create such a model. They propose that the BLR would not exist at all were it not for the accretion disk, and that evaporation at radii distant from the disk edge is responsible for the coronal distribution of the plasma. As will be shown below, this is consistent with the unification paradigm of AGN.

Accretion Region Dynamics

Here we briefly discuss some of the details related to the processes by which mass accretes onto the BH from the gaseous/

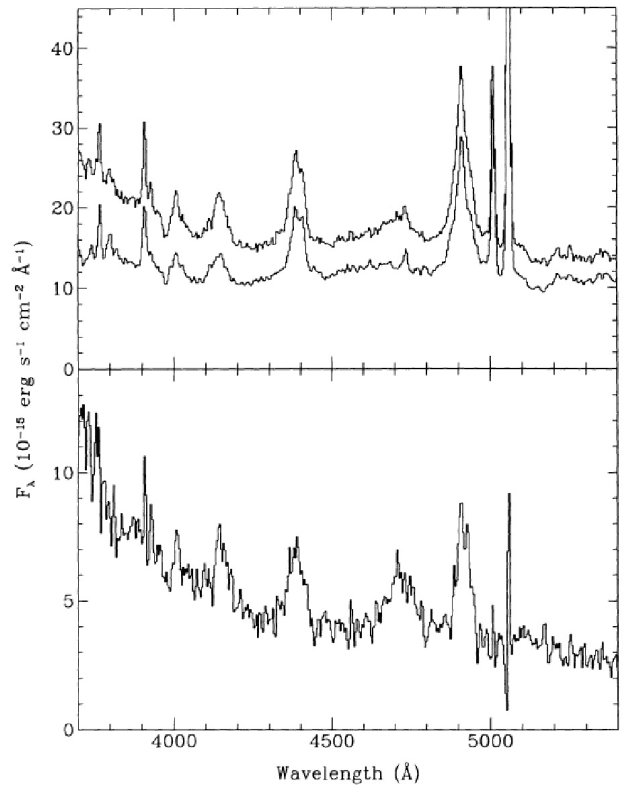


Figure 2: (a) Two optical flux spectra of an AGN BLR, taken 44 days apart. (b) The difference spectrum highlighting changes between the two spectra over this time period.[8]

dusty torus, in a manner consistent with the work of Czerny et al. (2004). While not directly related to our discussion, the most observationally consistent model of AGN variability (discussed in Self-Organized Criticality section) depends directly on accretion disk dynamics, so a qualitative review of some of the physics of mass flow in this region will be helpful.

Especially near the BBB, thermal excitement produced by proximity to the black hole leads to ionization of some of the constituent particles of the accretion disk. A non-negligible ionization in the disk implies that any truly accurate model of AGN variability must include, or at least acknowledge, contribution of magnetohydrodynamics (MHD) to the overall physics of the region, as it turns out that MHD (specifically, magnetic field interactions brought about by ionized plasma near the inner edge of the disk) can play a very dramatic role in both the structure and kinematics of an accretion disk.

The unification paradigm of AGN includes a minor stipulation for MHD-produced effects. Much like the work done by Czerny et al. (2004), it allows for magnetic flares (loops), running along the radius of the disk, perpendicularly to the plane. At some transition radius, usually at several Schwarzschild radii, these field lines open and give rise to the BLR corona. Furthermore, matter evaporation in the disk is prevented by magnetic field confinement, especially at long distances from this transition radius. As such, the toroidal structure of the cold disk is magnetically self-reinforced. Near the transition radius, however, open field lines produce the spheroidal (spherical?) distribution of the ionized gas stripped from the edge of the accretion disk. (This is, of course, an oversimplified generalization of a complicated system, so we refer you to Czerny et al. (2004) for a more detailed description).

To close this section, let us briefly review some of the quantitative timescales intrinsic in the NLR and BLR.

Assuming generally Keplerian accretion flow, we know from Czerny et al. (2004) that the dynamical timescale of gas and dust within the disk will be given by

$$t_{\rm dyn} = \sqrt{\frac{GM}{r^3}} \tag{2}$$

where $M = M_{BH}$ and $r = r_{BH}$. This is the Keplerian frequency, equivalent to the orbital period of an object in orbit of the BH. From this, we may obtain a generalized timescale for the radial propagation of sonic fronts with respect to the BH, namely

$$t_{\rm sound} = t_{\rm dyn}\left(\frac{r}{h_{\rm disk}}\right) \tag{3}$$

where h_{disk} is the thickness of the accretion disk through which the front is passing.

Thermal timescales are important as well, especially given our reliance on AGN spectra. Quantitative understandings of disk temperatures require familiarity with the thermal timescale of the region, which we define as

$$t_{\rm therm} = \alpha^{-1} t_{\rm dyn} \tag{4}$$

where α is related to the viscosity in the disk and is ~0.1. The viscous timescale, then, strongly resembles (3) and (4), in that it is directly proportional to another timescale, specifically

$$t_{\rm visc} = t_{\rm therm}\left(\frac{r}{h_{\rm disk}}\right)^2 \tag{5}$$

Despite our brevity in this section, the timescales surveyed above play a vitally important role in testing theoretically generated variability models, some of which are described in the following section.

AGN Variability Models

The majority of AGN exhibit at least some degree of wavelength-specific flux variability, particularly in the optical/UV (See Figs. 2 and 3).[1] By this virtue alone, it becomes apparent that a solid, well supported variability model would eventually become a part of the AGN unification paradigm, making our understanding of AGN structure and dynamics all the more complete.

Furthermore, if extreme cases of AGN nonetheless remain consistent with this paradigm, then the extreme variability mechanisms present in these objects must also be consistent with the lower-energy processes in more common AGN. SDSS J124602.54+011318.8, for example, has such high variability that it was once mistaken for a gamma ray burst afterglow.[6] Regardless, it must still be explained by a model capable of explaining less dramatic examples. In light of this, we now present a discussion of several such models for AGN variability, and briefly comment on the physical rationality behind the theories.

Self-Organized Criticality

One of the most promising AGN variability models in the field today is based upon the principle of self-organized criticality (SOC), an idea so elegant in its universality and powerful in its simplicity that it can explain something as complex as AGN luminosity fluctuations, as well as something as simple as the shape of a pile of sand.[7]

Quantitatively, AGN power spectral densities (PSDs) mimic declines well modeled by power laws in bluer ends of the spectrum. Specifically, these declines follow the trend

$$\frac{1}{f^{\beta}} \qquad (6)$$

where f is frequency and β is a constant of order unity, between ~1 and ~2. Amazingly, this type of variation is widespread in nature, and can be observed in Earth's weather patterns, the behavior of flowing water, and even Mozart's orchestral compositions.[7] Unsurprisingly, then, this power law fluctuation also appears in X-Ray binary spectra, such that they share two properties in common with AGN (the other being the BBB). However, it is known that X-Ray binaries and AGN vary in different ways, so similarities between the two end here. X-Ray binary variability arises from abrupt, dramatic events called flares (or "shots"). AGN lightcurves, on the other hand, vary with smooth, continuous dips and inclines. (Note the near symmetry of the two spectra in the top panel of Fig. 2). Explaining this seemingly contradictory observation is a valuable beginning to modeling AGN variability mechanisms.

It turns out that SOC is inherently connected with $1/f^{\beta}$ variation, so much so that an avalanche of snow on a mountain will liberate energy with $1/f^{\beta}$ fluctuations, once a certain critical slope is met, (dependent on the physical properties of the snow).

In a qualitative sense, describing an AGN accretion disk as snow on a mountainside appears to be a physically reasonable comparison. Both disk and snow are under the influence of a gravitational potential – whether that potential is generated by a black hole or the gravitational pull of the Earth is inconsequential. Both are governed by SOC, in that they spontaneously reorganize their structure to attain progressively lower energy and higher entropy.

In this model, then, AGN variability is produced by a series of self-reorganizations ("avalanches") within the accretion disk. The amount of matter accreting on the black hole is thus time dependent, and increases for a short period of time after a disk reorganization. Because this model is based on the principle of SOC, the resulting luminosity fluctuations predicted by the model follow $1/f^{\beta}$ variation, consistent with observed data. Furthermore, the model is consistent with the timescales discussed in Accretion Region Dynamics section as, for an unstable disk, reorganizations can occur at a relatively rapid-fire pace, enough so that the model can almost satisfactorily produce the short, large amplitude variability profiles of extreme-case AGN like NGC 4395. Conveniently, the SOC model can also be adapted to explain observed variability in X-Ray binaries, and we refer you to Mineshige & Yonehara (2001) for an excellent discussion of the model's interplay between these two systems.

Figure 3: NGC 4395: The diamond in the rough?

Of the multiple paradigms of AGN variability, those based upon simple, physically consistent ideas are always the most attractive. As SOC is a predominant process in nature, we are inclined to consider this model as the best start toward accurately describing the processes occurring within the accretion disk. As with all nascent models, however, this is a gross oversimplification of the actual system, as it ignores any effect of MHD, which must be an important part of any "hot accretion disk" theory (discussed in Accretion Region Dynamics section).

Though we have paid most attention to what appears to be the best candidate for an AGN variability mechanism, we now present a brief discussion of other recently developed models.

Other Models

The majority of variability models are based upon some connection to a time-dependent parameter in the accretion region. This makes sense, because a discontinuous accretion rate is the simplest, most physically reasonable method by which to drive luminosity fluctuations in the region surrounding a black hole. This is the principle surrounding the theory of X-Ray irradiation. This model is dependent upon response times in disk layers, as well as time lags in reflected versus direct X-Ray emission from the BLR, a parameter dependent upon extinction in the foreground and observation angle. As with the SOC model, this theory is sound and well-supported by observation, so much so that it probably plays a somewhat substantial role in AGN variability. Unlike SOC, however, it is not stand-alone in that it cannot produce extreme variability patterns, like those observed in NGC 4395 and hundreds of other objects, like SDSS J124602.54+011318.8.

Of course, one must ask whether variability in AGN is an intrinsic process at all, or merely a trick of the eye; an artifact of observation angle and foreground obscuration. The question is legitimate, and these effects most likely play at least a non-

JD −2,440,000	J	H	K	L
8576..............	11.33	10.43	9.71	8.32 ± 0.06
8593..............	11.41	10.52	9.76	8.37 ± 0.11
8629..............	11.33	10.44	9.70	8.40 ± 0.05
8630..............	11.37	10.44	9.71	8.35 ± 0.06
8632..............	11.33	10.44	9.70	8.32 ± 0.06
8633..............	11.35	10.43	9.70	8.34 ± 0.06
8634..............	11.34	10.45	9.71	8.37 ± 0.05
8671..............	11.35	10.46	9.69	8.34 ± 0.06
8674..............	11.32	10.42	9.67	8.29 ± 0.06
8675..............	11.32	10.41	9.65	8.23 ± 0.06
8700..............	11.40	10.45	9.70	8.39 ± 0.06
8727..............	11.33	10.43	9.69	8.34 ± 0.05
8731..............	11.34	10.45	9.72	8.31 ± 0.06
8733..............	11.35	10.43	9.69	8.38 ± 0.06
8734..............	11.33	10.45	9.70	8.39 ± 0.06
8735..............	11.24	10.44	9.72	8.30 ± 0.06
8768..............	11.28	10.47	9.72	8.36 ± 0.05
8783..............	11.17	10.39	9.65	8.31 ± 0.06
8786..............	11.09	10.27	9.62	8.32 ± 0.06
8789..............	11.16	10.34	9.60	8.32 ± 0.08
8790..............	11.07	10.27	9.58	8.24 ± 0.06
8792..............	11.16	10.35	9.63	8.27 ± 0.06
8804..............	11.13	10.29	9.59	8.22 ± 0.05
8834..............	11.20	10.35	9.60	8.26 ± 0.05

Table 1: Near-IR fluxes over a 258 day period[8]

negligible role, but by no means can they hold up to the wide range of observed AGN spectra.

In reality, the most accurate model would probably be a combination of the above three paradigms, and would probably be based upon physically simple theory, much like SOC.

Discussion

In fields as young and vibrant as AGN physics, qualitative survey papers such as this discussion are most useful when they provide scientific motivation for further research. In this paper, we surveyed the unified model of AGN in terms of its theoretical structure, observed properties, and quantitative timescales. Having described this environment, we then presented several AGN variability models, consistent with the unification paradigm, which must exist in this environment in order to produce the sometimes dramatic luminosity fluctuations observed in nearly all AGN.

Models like these are difficult to generate, because AGN are very far away, and so we cannot observe their inner structures. If, however, we are able to constrain at least a few parameters of AGN physics, our variability models improve along with the unification paradigm as a whole. Currently, the best way to do this is to study extreme cases of AGN, like NGC 4395, the uniqueness of which allows us access to quantitative data hitherto out of reach in more common specimens.

It is the hope of the author that research will continue along these lines.

1. Czerny, B., A. Rózanska. and J. Kuraszkiewicz. "Constraints for the Accretion Disk Evaporation Rate in AGN from the Existence of the Broad Line Region." 2004, arXiv preprint (astro-ph/0403507)

2. Chen, K., and J. P. Halpern. "Structure of Line-emitting Accretion Disks in Active Galactic Nuclei." Astrophysical Journal 344 (1989): 115.

3. Peterson, B. M., and K. Horne. "Reverberation Mapping of Active Galactic Nuclei." 2004, arXiv preprint (astro-ph/0407538)

4. Antonucci, R. R. J. "Unified Models for Active Galactic Nuclei and Quasars." Annual Review of Astronomy and Astrophysics 31 (1993): 473.

5. Quillen, A. C., S. Shaked, A. Alonso-Herrero, C. McDonald, A. Lee, M. J. Rieke and G. H. Rieke. "The Variability of Seyfert 1.8 and 1.9 Galaxies at 1.6 microns." 2000, arXiv preprint (astro-ph/9912451)

6. Gal-Yam, A., E. O. Ofek, A. Filippenko, R. Chornock and L. Weidong. "SDSS J124602.54+011318.8: A Highly Variable AGN, Not an Orphan GRB Afterglow." 2002, arXiv preprint (astro-ph/0202354)

7. Mineshige, S., and A. Yonehara. "AGN Variability in the Context of Self-Organized Criticality." Astronomical Society of the Pacific Conference Series 224: Probing the Physics of Active Galactic Nuclei 2001: 87.

8. Stirpe, G. M., et al. "Steps Toward Determination of the Size and Structure of the Broad-line Region in Active Galactic Nuclei. 6: Variability of NGC 3783 from Ground-based Data." Astrophysical Journal 425 (1994): 609.

9. Zheng W., G. A. Kriss, R. C. Telfer, J. P. Grimes and A. F. Davidsen. "A Composite HST Spectrum of Quasars." Astrophysical Journal 475 (1997): 469.

Grant Tremblay will graduate with a B.S. in Physics and Astronomy in May, 2006. He has worked with Dr. Alice Quillen for three years and plans to continue the collaboration through graduate school, where he intends to complete a Ph.D. in Astrophysics. He plans for a career in research.

Ball Catching and the Role of Prediction

Keith Gorgos, 2006

Advised by Mary Hayhoe, Ph.D.

Department of Brain and Cognitive Sciences

How do we use our eyes on a daily basis for normal vision? Most people never even stop to think about how their eyes work to guide their actions during their daily routines. If they did, they may discover that vision is a highly specialized process. The eyes are constantly moving from location to location, seeking to acquire selective information about the world. Very little was known about how the eyes accomplished this until recently, when eye-tracking devices robust enough to allow unrestrained body movements were introduced. It has been shown in a number of everyday activities such as driving, table tennis, cricket, and reading that eye movements are highly specialized for the task at hand.[1,3,4] This specialization suggests that eye movement patterns are not generated reflexively by the nervous system, but must be learned. The current paper investigates this aspect of eye movements. It has been previously shown that retinal motion, stereo information, and extra-retinal information from pursuit eye movements are important in the task of catching a ball. Stereo information is the result of a disparity produced through the integration of the left and right eye images and enables the perception of depth. Extra-retinal information includes knowledge of where the eye is positioned in the head (i.e. what direction the eye is pointed). Pursuit eye movements can be thought of those eye movements that occur when athletes "keep their eyes on the ball". To further explore how our eyes are used to aid the accomplishment of daily living, we examined subjects' eye, hand, and head movements as they caught balls thrown with a bounce. Furthermore, we examined the subjects' head and eye movements as they threw balls to others and also as they observed two other individuals throwing and catching. Our investigation was an exploratory study in which we hoped to compare to previous studies and findings. We were looking to determine how we learn to make the predictions that are so necessary to our normal vision on a daily basis.

Our Approach

We examined this question by observing where the visual fixations occur, what visual information is needed in the activity, how specialized the eye movements were, whether or not there were any random or exploratory eye movements, and how the hands and head movements were coordinated.

Eye, head, and hand movements were recorded while subjects caught, threw and observed balls thrown with a bounce. Subjects' eye movements and the view of the scene ahead were recorded with a head mounted eye-tracking camcorder. The image of the eye as it moved was recorded and embedded into the corner of the live scene image, which displayed the playing field from the subject's point of view. This was advantageous to our analysis as it allowed us to see what the eye was doing at the same time we could examine the action in the field. The foveal direction of the eye (the fovea is a small area on the retina where fixations fall) was detected by the tracker and superimposed as a crosshair onto both video images of the eye and scene ahead. This direct mapping of the crosshair onto the image was very beneficial, as it allowed us to easily see complicated events as they took place, as opposed to a simpler eye-tracking device which would have just produced a list of coordinates. The image from the head mounted camera can be seen in figure 1a. Subjects were also recorded with a fixed scene camcorder, so that any activity in the field that occurred off the head camera could be obtained by matching the two video time stamps.

Hand movements were detected and recorded by two coordinate-tracking gloves worn by the subject. One glove was particularly specialized so as to measure the changes in the position of the subject's fingers, such as when the fingers closed to make a catch.

Head movements were detected by using a stationary reference point in the field of view and observing when the field in the camera frame shifted. By measuring the distance the frame moved in regards to the reference point, the direction and magnitude of head movements were recorded.

Experimental Task, Condition & Setup

Each subject began the experiment bouncing a tennis ball off a wall with throws that bounced once, hit the wall, and returned to the subject. To some extent, this familiarization period enabled each subject to adapt and become accustomed to the properties of the tennis ball as well as the tasks of throwing and catching. A bouncy ball was not used during the familiarization period. This was done so that when it was introduced for the second half of the experiment, participants would be unfamiliar with its properties. This enabled us to see how the ability to pursue a ball depends on the experience with

Figure 1a: A typical image from the head mounted camera

Figure 1b: Field configuration with 3 players

a ball's dynamic properties.

Following the familiarization period, the subject and two other non-subject players were positioned in the field in the shape of a triangle, with each person as a "point" of the triangle, as seen in figure 1b. Players threw the ball with one bounce to the other players in a clockwise direction for the duration of the experiment. A tennis ball was used for the familiarization period (against the wall) and for the first half of the triangular sequence. For the second half, a bouncy ball that was slightly smaller and faster was used. In the triangular arrangement, three conditions were examined as the ball went around the triangle, Catching, Throwing and Observing (a throw and catch).

Results & Discussion

Catching

The first six tennis ball trials and the first six bouncy ball trials were analyzed for all five subjects. As found in cricket batsmen preparing to hit a ball, subjects' eyes fixate on the hands of the thrower preceding a catch, make an initial saccade (a rapid eye movement) to the region of the anticipated bounce point, and then pursue (follow closely) the ball until just before it reaches their hands.[4]

In order to examine the nature of the eye movements as the subjects caught the balls, we closely compared the time at which important events occurred with the time of the subject's eye movements. Our results showed that all of the initial saccades (towards the predicted bounce point area) occurred at a latency of 133ms or less, in comparison to the release time from the hand. (A latency is the amount of time between a stimulus and a response.) It is known by vision scientists that it takes 200ms to initiate a saccade based upon external stimuli. Thus, if an actual saccade occurs sooner than 200ms after an event, that saccade was most likely made in anticipation of that event that required the saccade. Therefore, the saccades we observed were anticipatory in that they were based upon a prediction of where the ball would go. This is further emphasized by the fact that a number of the saccades even occurred before the release, some as much as 67ms before (a "latency" of -67ms). The average latency between t_R (time of the release) and t_S (start time of the saccade) for all five subjects in both tennis and bouncy trials is plotted in figure 2.0. While it may seem simple to say subjects "predict" or make "anticipatory" eye movements, it is a process of greater complexity than one may first realize. People do not usually realize the complexity of making predictions, because they are not even aware that predictions are being made: the brain does them almost automatically. Before someone can make an anticipatory saccade, they must combine the informative visual stimuli of the trial with predictions of the ball's speed, and other predictions of the ball's properties. As people gain more experience, they "automatically" become better, but how?

In the tennis trials, there is no decrease in the t_R - t_S latency as the number of trials increased, which is likely due to "familiarization period" in which participants became familiar with the properties of the tennis ball. However, the drastic decrease in the latency during the bouncy condition (saccades occurring much sooner over the trials) was rather striking. This suggests that subjects are adapting and learning with experience to the new ball's properties. This was shown by their increasing ability to anticipate and predict events, enabling them to become more successful in the task in terms of pursuing the ball. It seems as if the eye is trying to get itself into position at the bounce point sooner so that it can react to the ball off the bounce sooner, or have more time to adjust its gaze correctly. So how exactly are the subjects able to "get better" and constantly refine their actions? Our observations

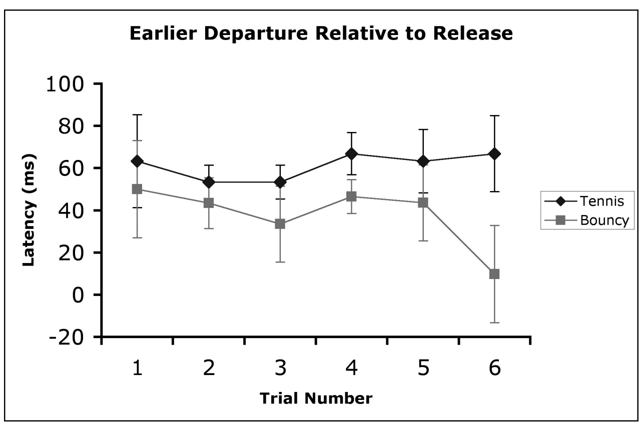


Figure 2.0: Earlier departure relative to release

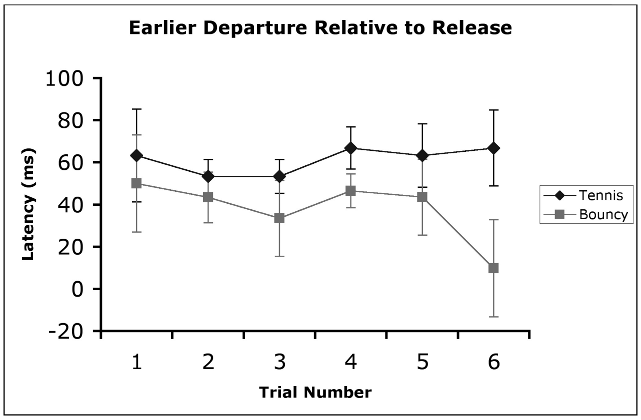


Figure 3.0: Earlier departure relative to release

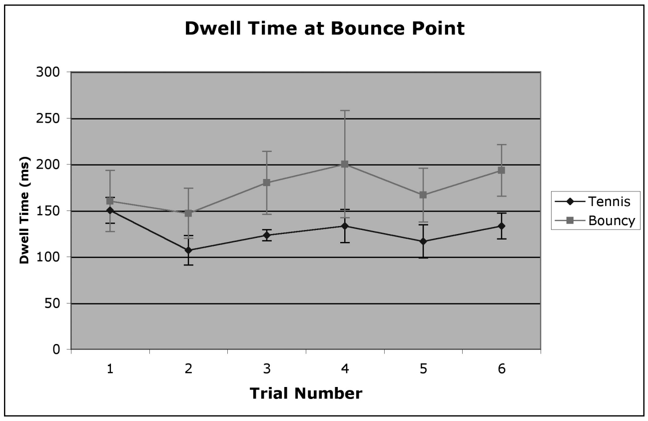


Figure 4.0: Dwell time at bounce

suggest that people maintain an internal model of the dynamic properties of the world, and rapidly update this model when errors occur. After experiencing errors on the first few trials (especially with the new bouncy ball), the subjects appear to have updated their internal model of the ball's dynamic properties, based on their recent experience with the newer ball.

The concept of an internal model is based on the idea that people have internal, perceptual representations of the physical world around them. When people receive visual and other sensory information regarding the properties of the objects in the physical world around them, the central nervous system processes this information and rapidly updates their current perceptual representations of the world.[5] When errors occur in the present task, it is a signal to them that their current representation is "outdated", and revisions need to be made.

We also compared the end time of the saccade towards the bounce point (t_E) to the time the ball bounced (t_B), producing the latency of (t_B -t_E), as shown in figure 3.0. The end of the saccade can also be thought of as the start of the fixation near the bounce point. As shown by the graph, however, there is no real "latency", as all the latencies are negative. In other words, saccades reached the region near the predicted bounce before the bounce occurred. For both conditions, as the trials continue, there is a small downward trend in t_B -t_E suggesting that experience with catching causes a slightly greater anticipation of the bounce event (the latency becomes more negative). This is especially true for the bouncy condition, as the anticipation becomes greater at a much faster rate; the latency for the tennis trials decreases by an average of 33 ms, while the latency for the bouncy trials decreases by an average of 80 ms. That is, the saccade to the bounce point was arriving at its end position sooner for the bouncy trials.

The suggested conclusion is that as subjects gain more experience, they learn to anticipate faster. Due to errors they have made in tracking the ball, subjects feel a need to improve their anticipation of the bounce point. We believe they do this by subconsciously updating their perceptual models to the standards necessary to eliminate errors, based on the integration of visual and temporal cues with their prior experiences. The demand for this anticipation is increased when a newer, faster (bouncy) ball is introduced that travels 19 visual degrees faster. Thus, with the bouncy trial, because the participant realizes this drastic change in properties the anticipation becomes quicker, and at a faster rate. Due to prior experience with the tennis ball, the "adjustments" made in the tennis trials involve more "fine-tuning" as opposed to the rapid adjustments made for the bouncy trials. The greater anticipations made in the bouncy trials enable subjects to have more time fixated near the bounce point, gathering information from the approaching ball. In addition, while the gaze may be fixated above the anticipated bounce point, the subject's attention may be directed towards the ball in motion or on the actual bounce point. Thus, subjects may be gathering information through attention, while preparing for the next pursuit movement with the position of fixation.

The observations of anticipatory saccades that reached the bounce point region prior to the bounce, the saccades that anticipate the release from the hand, and the ability to predict the actual location of the bounce point demonstrate how essential prediction is to this ball catching activity. By arriving at the bounce point ahead of the ball, the subject has time to prepare for the change in direction and speeds caused by the floor at the bounce. If the gaze were to try and pursue the ball before the bounce point, it would probably overshoot the ball when the ball bounced, and have to correct for the error. By saccading ahead to a position in the ball's path beyond the bounce, it avoids the possibility of being thrown off by the bounce.

Once a subject's saccade brought his gaze to the bounce point region, fixation remained there for a length of time after the bounce, after which he began pursuing the ball with his gaze, a time referred to as t_P. This delay was referred to as the dwell time at the bounce point, or t_E - t_P, and is depicted in figure 4.0. The dwell time for the tennis trials seemed to stay fairly constant throughout the trials, while the bouncy trials demonstrated a more interesting pattern. The dwell time of the first bouncy trial is very close to the preceding tennis trials, but as the bouncy trials continue, the dwell time increases further, eventually becoming 65ms greater than the last tennis trial.

Although the increase was not statistically significant, due to large SEMs, the dwell time at the bounce point for the bouncy ball increased as subjects had more experience with the ball's dynamic properties. The additional dwell time could be partially attributed to the faster anticipation to the bounce, allowing a longer dwell time. Additionally, it is possible some of the additional dwell time was a result of the pursuit movement (which occurs after the dwell time) starting later. Either way, it seems the oculomotor system may require more time to respond to and start its attempts to pursue the bouncy ball than it did for the slower tennis ball, to which it had already adapted. However, to determine if there is actually an increase that can be considered statistically significant, additional participants in these tasks should be examined.

The subject's fixation direction at the time of the bounce point (t_B) was recorded for all subjects in both tennis and bouncy trials, for which the results were very similar. Only 4 out of the total 36 fixations for the tennis trials were below the bounce point. Bouncy trials displayed similar results, with only 3 of 36 trials below the bounce point.

For 90 percent of all trials, the fixations during the bounce were above the bounce point–gaze was directed a mean of 5.9 visual degrees above the bounce point for all trials. Our results were similar to table tennis players whose saccades are "[…] clearly aimed just above the bounce point", as found by Land and Furneaux in 1997.[3] Table tennis players directed their gaze an average of 5.3 degrees above the bounce point, with at least 90% of the fixations occurring above the bounce point as well.[3] A possible reasoning for positioning foveal direction just above the anticipated bounce point is that it reduces the distance the gaze will be "out of position", as compared to the foveal direction if it were directed under the bounce point. In other words, by positioning foveal gaze just above the bounce point, the eye can always wait for the ball to rise up to its position to resume tracking. On the other hand, if the subjects tried to position their gaze at the bounce point itself, or under the bounce point, they would be increasing the distance across which they would need to make a saccadic 'catch-up' movement in the event of a positioning or speed prediction error. By keeping the gaze just above the bounce point, a positioning error will never put the gaze behind the ball at the bounce. Gaze positioned above the bounce always has a chance to resume tracking the ball as it rises up to its position and does not have extra ground to cover due to a fixation below the bounce.

Following the dwell time at the bounce point, subjects attempted to track the ball using smooth pursuit gaze movements. (These are a special class of eye movements driven by specialized neural circuitry that is thought to respond to image motion on the retina by an attended object.) However, accuracy depended on the experience with the properties of the ball. In order to compare the accuracy of these pursuit movements, we examined the position of the subject's gaze frame by frame and found the percentage of frames at which the subject was successfully pursuing the ball. That is, the frames when their gaze was directed on the ball (within a region of about 1.5 visual degrees).

As shown in figure 5.0, the subjects' accuracy with the tennis ball, is fairly stable. However, in the first bouncy ball trial, as shown in the figure, there is a drastic drop in accuracy of the pursuit in comparison to the sixth tennis trial. ($t(4) = 3.14$, $p<0.05$). As the number of bouncy trials increase, however, there is a great deal of improvement, with the accuracy with the bouncy improving to be nearly equal to the accuracy of the early tennis trials. The accuracy on the last bouncy trial was found to be statistically greater than the first bouncy trial ($t(4) = 2.83$, $p < 0.05$).

In general, during the pursuit period following the bounce, the majority of tennis trials involved no saccades. Following

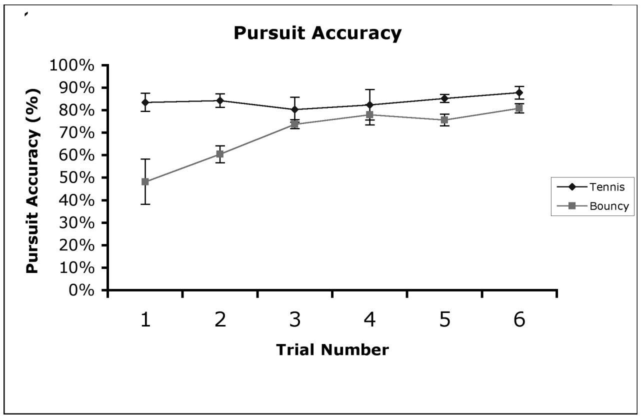


Figure 5.0: Pursuit accuracy

the (tennis) bounce, there was usually a short period of 'catch-up' pursuit in which a small gap between the ball and the gaze decreased, which was followed by a period of smooth pursuit in which the gaze accurately tracked the ball until it was close to the hands. In the later trials of the bouncy condition, this pattern was also very common. During the early bouncy trials, however, there was usually a large 'catch-up' saccade, followed by a number of smaller saccades, until the gaze was repositioned on the ball. Once the subject 'caught-up' (near the end of the ball's flight), they generally displayed some form of smooth pursuit movements (which tended to be 'shakier' and shorter than the tennis trials or later bouncy trials). The first saccade on the first bouncy trial was generally the largest: one subject's first saccade reached 11.7 visual degrees. Additionally, some subjects were never able to begin a period of smooth pursuit on the first trial –all their attempts to track the ball consisted of saccadic behavior. However, by the sixth bouncy trial, subjects were tracking the ball in a pattern similar to the tennis trials.

If subjects had experience with the properties of a ball, as they did with the tennis ball, and as they did with the later bouncy trials, they used smooth pursuit gaze movements to track the ball. However, they were forced to make 'catch-up' saccades on some of the trials when errors in their tracking occurred. The largest of saccades occurred on the first bouncy trials, when subjects had the least amount of experience and adaptation to the faster ball. This is parallel to the results found by Land and McLeod when examining cricket, who stated, "'catch-up' saccadic behavior is expected of someone who has not played cricket."[4] As trials and experience increased, the number and magnitude of saccades decreased, signifying a reduction in tracking errors. At the same time, smooth pursuit movements increased and the percent accuracy of these movements became more accurate. These changes in eye movements suggest that the subjects were rapidly updating their internal models of the world based on the ball's dynamic properties.

Throughout our analysis of the aspects of the catching trials, we saw a continuing pattern. Few errors and few adjustments were made to the eye movements during the tennis trials, while continuous adjustments were made as the result of errors during the bouncy trials. We discovered that success in the task of catching a ball is more complex than simply responding to visual cues. We learned that you can not keep your eye on the ball unless you have an accurate representation of the ball's properties, and can integrate this information with the

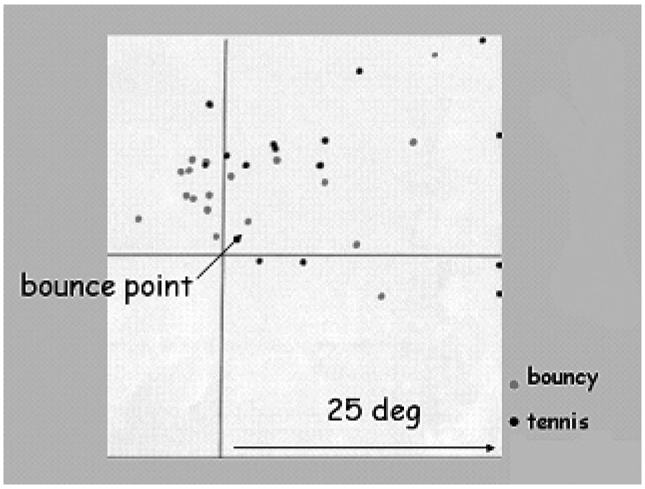


Figure 6.0: Scatter plot of fixations near bounce

current visual stimuli. We believe this may be done through an internal model.

Observing

While the main focus of the experiment was on the catching aspect, eye movements were also recorded as subjects watched the throws between the two other players. The gaze and anticipatory patterns observed were task specific to the observing trials, as the patterns differed from the catching trials.

Similar to catching, when subjects watched another thrower and catcher, they made a saccade somewhere near the anticipated bounce point. The anticipation of the bounce point was much less accurate for observing trials, as shown in Figure 6.0, than it had been for the catching trials. As with catching, fixations were generally above the bounce point itself: 25 of 30 fixations (83%) were above the bounce point. However, fixations were spread across the horizontal axis much more than they had been in the catching. This is most is likely because the observer is not required to be as accurate, as the observer has nothing to do with making the catch successful. Thus, his eye movements do not gather as much information as they do in the catching trials. This is also probably why there was very little pursuit movement in the tennis trials. The observer is not making many errors pursuing the tennis ball, and thus is fairly "relaxed" in terms of gathering information. In other words, the observer already has knowledge of the ball's dynamic properties, and is having little trouble pursuing the tennis ball in the catching trials. Thus, it is possible that the observer does not feel a need to gather more information regarding the properties of the tennis ball as it goes between the two other individuals. Conversely, subjects were much more likely to pursue the bouncy ball when observing others.

Subjects in the bouncy trials pursued the ball somewhat after the bounce in about 83% of the bouncy trials compared to 22% in the tennis trials. This is likely because the subject was not familiar with the dynamic properties of the bouncy ball and thus, was trying to use the observation trials to learn the new properties of the bouncy ball. This gives more support to the concept that subjects may have an internal model that they are trying to update their when errors occur.

As in the catching trials, subjects made anticipatory saccades relative to important events in the balls path. Head movements also predicted these events. In general, anticipations on the observing trials were much greater than those on the catching trials. Again, this may be because subjects are not involved in the task themselves and thus are more willing to make "higher risk" predictions, as their "success" in observing is not that important.

Throwing

Analysis of throwing trials was not as extensive as the catching or observing trials, although interesting results were found nonetheless. The gaze and anticipatory patterns observed were much different than those seen in the observing and catching trials. When subjects threw the ball, they displayed a different pattern of movements, first making a saccade to a point on the floor beyond of the bounce point, and then to the catcher's hands, with both saccades preceding the ball by several hundred milliseconds. The fixation made just beyond the bounce point may serve to gather two pieces of information that allow the subject to throw the ball accurately to the other player. It is possible the fixation is positioned between the catcher's feet and the anticipated bounce point so that the thrower can easily switch attention back and forth between the two points and make an accurate throw. Attention to the feet allows the thrower to see the total distance the ball needs to go, while attention to the anticipated bounce point allows the user to see where he aims to throw the ball. The anticipatory saccades that precede the events in the throwing trials additionally demonstrate the importance of prediction for visual activities.

Overall

Throughout our observations of catching, observing, and throwing, we saw just how important predictions are to the current task. As stated earlier, it takes 200 ms to initiate a saccade based upon external stimuli. Thus, without predictions of the anticipated ball movement, the eye would not be able to track, or 'catch-up' to the ball's movement, as solely reactive behavior would leave the gaze behind the position of the ball, not on the ball as we saw with the tennis, and later bouncy trials. We also saw that when the properties of the physical world change, people are more likely to make errors. Errors indicate that there is a need to update one's internal representations of the physical world, which allows us to make necessary predictions for visual tasks. This was demonstrated by the reoccurring pattern of adjustments being made to the eye movements for the bouncy trials. While the current investigation did not focus on the effect of the changes in latencies and gaze durations in performing successfully physically (i.e. making a successful catch as opposed to dropping it), it seems the proactive nature of our visual system prefers to be as efficient as possible. Rather than constantly having to 'catch up' to a moving object and recalculate saccadic movements based on errors, individuals prefer to be more efficient. That is, they prefer to establish smooth pursuit movement early on. By increasing the dwell time and decreasing the t_R - t_S and t_B -t_E latencies, it seems as if the participants desire to arrive to the fixation point near the bounce sooner. Unlike a saccade, a fixated eye allows new information to be gathered from the world. Thus, getting to the fixation point sooner allows the eye more time to be prepared for the approaching ball and observe its position and speed. It seems likely that this would enable the eye to begin smooth pursuit more accurately than a fixation that arrived later and did not allow for much information gathering. It seems likely that accurate smooth pursuit is preferred to multiple 'catch-up' saccades, as the saccades involve multiple calculations that try to estimate the next position of the ball's path at which the ball can be intercepted to resume smooth pursuit. Smooth pursuit, on the other hand, seems fairly easy to maintain, once it has been established, as it simply involves maintaining the current speed of movement. Thus, while it has not been proven by our experimental results, it is a possibility that changes are made in the latencies and dwell time so that more time is allowed in a state of fixation, when information can be gathered. This seems as if it would help to establish smooth pursuit earlier so less attentional resources are used in tracking the ball, as constant 'catch-up' calculations would not be necessary. On the other hand, during the tennis trials, few errors or adjustments were made and it seems likely that subjects may have established an accurate internal model from prior experience in the familiarization period.

Conclusion

It has been shown in that past that a number of everyday activities require highly specialized eye movements for the task at hand.[1,3,4] This specialization suggests that eye movement patterns are not generated reflexively by the nervous system; rather, they must be learned. We investigated this aspect of eye movements and our findings demonstrate that vision cannot be a solely reactive system, but instead, must involve complex, proactive processes, that acquire information from the world essential to daily activity by anticipating events rather than reacting to them. From our analysis of subjects catching, observing others throw, and throwing balls with a bounce, we see that eye movements are highly specific to the task at hand, supporting a number of experiments done previously regarding such activities as cricket, table tennis, driving and reading music.[1,3,4] While all task variations involved the similar condition of a ball thrown to someone with one bounce, the eye movements still changed when the actual task (catching, throwing, or observing) itself changed. One thing, however, was apparent throughout the trials: the eye movements were constantly proactive, attempting to gather information from the environment rather than reacting to it after the event occurred. Our analysis suggests that by anticipating events, observers position their bodies in ways that allow them to gather essential information to the current task. The notion of proactive eye movements has also been supported by other studies, including those by Land and Furneaux in 1997 and Flanagan and Johnson in 2003.[1,3]

The patterns of eye activity we observed were similar to those found in cricket by Land and MacLeod, who showed that anticipating the position of the bounce point is important for intercepting the ball with the bat and similar to those found in table tennis by Land and Furneaux.[4,3] Our results show that prediction is a major factor in the task of catching a ball. In addition to the anticipatory saccadic eye movements, the head movements and pursuit movements we observed reveal that visual information is gathered so as to plan for a predicted state of the world.[2]

The findings of our research also suggest that people maintain a sophisticated internal model of the dynamic properties of the world (which seems necessary for continuity of behavior) and rapidly update this model by constantly comparing their internal model to the errors or accuracies that occur in their responses to stimuli.[2] As we gather visual and non-visual sensory information from the world regarding the present task, we refine the model so that we are able to plan ahead and act appropriately in future situations. This was shown by our results when we switched from the tennis ball to the bouncy ball during the catching trials. We saw that the ability to pursue the ball depended on experience with the ball's dynamic properties– when people have little experience with these properties, errors are made. After experience with the properties of the new ball, people were able to update their internal models based on the learned properties of the world. This enabled them to respond in a predictive, and thus more successful, manner that involved more accurate pursuit. Therefore, our results also support preceding studies that suggest prediction, which is dependent on proactive eye movements, plays an important role in our everyday activities –even if we may fail to realize it.

1. Flanagan, J.Randall, Johansson, Roland S. "Action Plans Used in Action Observation" Nature 424 (2003): 769-771.

2. Hayhoe, M. "The Role of Prediction in Catching Balls." Vision Sciences Society Convention. Sarasota, Florida. 4 May 2004.

3. Land, M. F., Furneaux, S. "The Knowledge Base of The Oculomotor System." Philosophical Transactions of the Royal Society of London. Ser. B 352 (1997): 1231–1239.

4. Land, M. F. & McLeod, P. "From Eye Movements to Actions: How Batsmen Hit the Ball." Nature Neuroscience 12.3 (2001): 1340–1345.

5. Loomis, Jack M. and Beall, Andrew C. "Model-Based Control of Perception/Action" Optic Flow and Beyond. Ed. Vaina L.M., Beardsley S.A., Rushton S. Boston: Kluwer Academic Publishers, 2004. 421-441.

Keith Gorgos will graduate with a B.S. in Brain & Cognitive Science in May, 2006. He worked with Professor Mary M. Hayhoe, Ph.D. for the duration of his sophomore year. After graduation, he is considering careers related to BCS, as well as the possibility of attending both Law and Business school, to further expand on the diversity of his education.

Members of the Class of 2005 who received distinction in research

Art History
Anna Christine Lessenger **

Biological Sciences: Cell and Development
Sharon Lynn Paige

Biological Sciences: Biochemistry
Varun Kumar Chowdhry
Crystal Rose McClain
Lisa Marie Span

Biological Sciences: Ecology and Evolutionary Biology
Erika Lea Logan

Biological Sciences: Neuroscience
Vanessa Suzanne Franco
Jason Todd Moore
Stacey Lee Poloskey

Brain And Cognitive Sciences
Katharine Amber Blackwell
Wendy Nicole Ressmann
Joseph C. Toscano

Computer Science
Peter Charles Barnum *

Economics
Geoffrey Robert Bowser
Zachary Ronald Fisk

English
Anne Elizabeth Cilano
Shari-Lynn Marie Cuomo
Lauren E. Duszlak
Catherine Ann Egan
Zoe Marie Kazmierski
Kerry Joy Linden
Michael John New
Allison Elizabeth Ogorek
Marissa An Ohira
Christian James Perticone
Sona Simran Kaur Rai
Katherine Roache
Akshina Ramesh Samtani
Charmaine D. Teodoro

Health And Society
David R. Friedmann
Rene N. Herbert
Zipporah-Lakshm Muna Inniss
Ajay Kuriyan
Kathryn Theresa O'Shei
Jordan Max Silberman

History
Robert H. Clemm
Katherine Way Goddard
Joshua Saul Josephs
Emily Klein Locker
John Conner McVay
Jesse D. Melman
David Paul Pascoe
Lauren E. Pulwer

Interdepartmental Studies
Christopher Allen Logan

Linguistics
Jill Caroline Thorson

Mathematics
Joseph Robert Galante

Modern Languages and Cultures: French
Rachele Cecile Haber-Thomson

Modern Languages and Cultures: German
Elizabeth Ann Boerman **

Music
Benjamin Ernest Thorburn

Philosophy
Lewis Michael Powell

Political Science
Thomas M. Hayes
Erica Lynn Owen **
Daniel Harris Wolf **

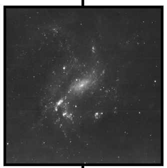
Psychology
Jason Matthew Adler *
Aparajita Biswas *
Joshua Mark Feldblyum
Kathryn Mary Rose Hefner
Angelina Marie Rayno
Amy Leigh Reger
Jennifer Marie Rodden *
Sarah Beth Schneider *

Religion
Heather Nicole Charlton
Stephanie Deborah Doan

A single asterisk (*) denotes high honors in research; a double asterisk (**) denotes highest honors in research.

Names are provided by the University Registrar's office. Many unlisted departments acknowledge outstanding scholarship through other means. High and Highest Honors are awarded on a department-by-department basis.

Picture References



HubbleSite Newsdesk and Allan Sandage, Carnegie Institution
http://imgsrc.hubblesite.org/hu/db/1993/19/images/a/formats/full_tif.tif

About the Journal

The Journal of Undergraduate Research (ISSN# 1547*9641), Volume 4, Issue 1, Fall 2005 was assembed on a Apple PowerMac G4 Quicksilver using Adobe InDesign CS. Graphics were produced using Adobe Photoshop 7.0 and Adobe Illustrator 10. Microsoft Office was used for text editing and review. Fonts used included Adobe Garamond, Futura, Times New Roman, and Symbol (for Greek characters). This 48-page journal was printed and perfectly bound by Mercury Print Productions Inc. of Rochester, NY.

jur