Lab Notes

NEWS FROM AROUND LINCOLN LABORATORY

BIOMECHANICS

Load-Sensing Boots

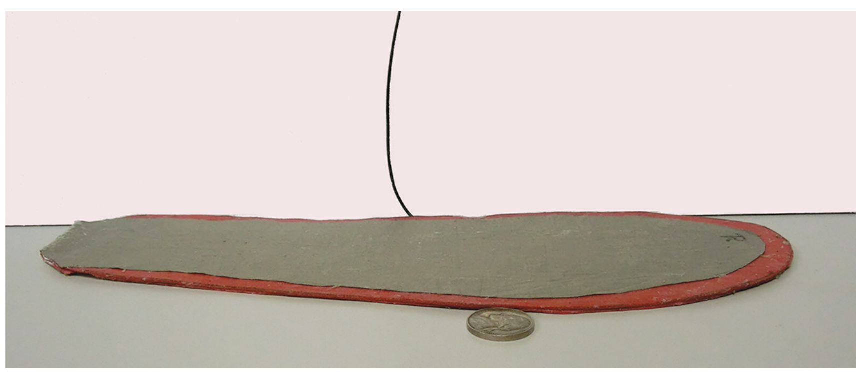
Instrumented footwear technologies present new possibilities for tracking and preventing lower-limb musculoskeletal injuries

We've all heard about a sprinter with a pulled Achilles' tendon, a gymnast with a stress fracture, or a football player with a meniscal tear. Consider any exercise and it is clear that overtraining and routine repetition involving a particular muscle group is a recipe for disaster. Such physical exertion is only intensified during military trainings and missions when swift movements and external forces continually place stress on the load-bearing bones and joints utilized in locomotion. Strap a 40- to 100-pound pack on a soldier's back and movements like walking, running, climbing, and even standing in place become much more taxing on the body, often resulting in the musculoskeletal injuries that are so prevalent among service members.

But if there were a way to quantify how much load, or weight, a soldier is carrying, and characterize the network of motions and forces that are involved, could such injuries be prevented? Joseph Lacirignola and Tadd Hughes, researchers in Lincoln Laboratory's Bioengineering Systems and Technologies Group, and fellow staff members Carlos Aguilar, Kate Fischl, Whitney Young, David Maurer, and David Aubin are studying this question of load dynamics. As part of a larger injury and physiological status monitoring program funded by the U.S. Army Research Institute of Environmental Medicine (USARIEM), the team is prototyping various sensor technologies to be integrated into military boots. These technologies, collectively referred to as the "load-sensor suite," are capable of determining how much weight an individual is carrying and where the weight is applying stress on the musculoskeletal system during both static and dynamic actions.

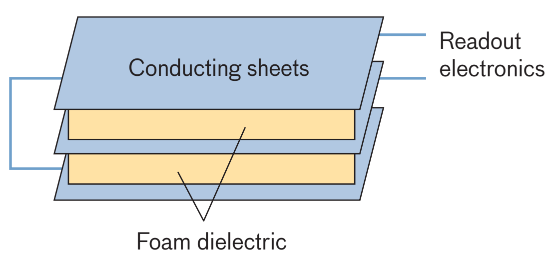
Currently, the load-sensor suite is made up of four prototypes:

- Capacitive load sensors—three layers of conducting sheets separated by two layers of insulative foam. The force exerted by stepping on a removable insole or incorporated midsole sends an electrical signal to a capacitance meter.
- Load cells—integrated components in a midsole sensing module



Capacitive load-sensor insole with readout electronics.

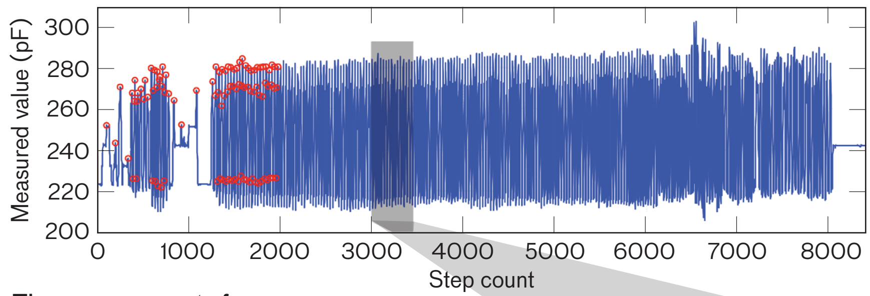
Layering structure of capacitive load sensor.

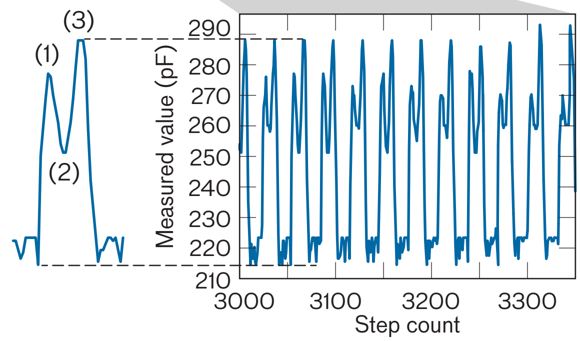


cushioned by a foam insert. Load-transfer plates feed the weight distribution from each foot into miniature load cells positioned at three discrete points: the heel, lateral midfoot, and ball of the foot (metatarsal) areas. Readout electronics are connected to an ankle monitor that supplies energy and stores data.

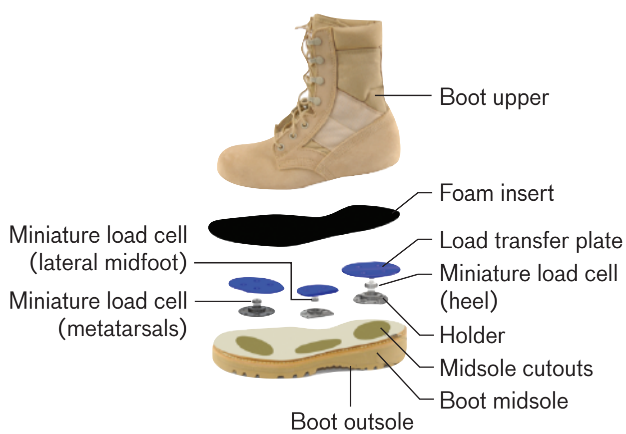
- Wave-spring strain gauges—stacked layers of wave washers (thin, disc-shaped rings) attached to a strain gauge and integrated into soles. The strain gauge senses changes in electrical resistance caused by movement and sends the signal to an ankle monitor.
- Wave-washer strain gauges—non-stacked wave washers attached to a strain gauge packaged into inserts with built-in electronics.

Combined with an accelerometer and gyrometer, the load-sensor suite systems can collect swing and stance dynamics, angles of impact, and accelerations. Analysis of these measurements can provide the military with valuable insights to correct injury-inducing practices. For instance, if results indicate an unbalanced gait, a soldier's pack may be lightened or repositioned to distribute weight more symmetrically. If the data show a particular movement is causing widespread injury among soldiers, training regimens can be adapted. Changes in the heel-to-ball force ratio may indicate increasing fatigue that can then be alleviated. As Hughes notes, "Tests over weeks and months with an average soldier carrying a 40-pound pack might give us an evaluation of how often he should be rested." Lacirignola similarly comments that the data can help determine "pound hours," or "how long one can last with a particular load and the resultant stress placed on the muscles."



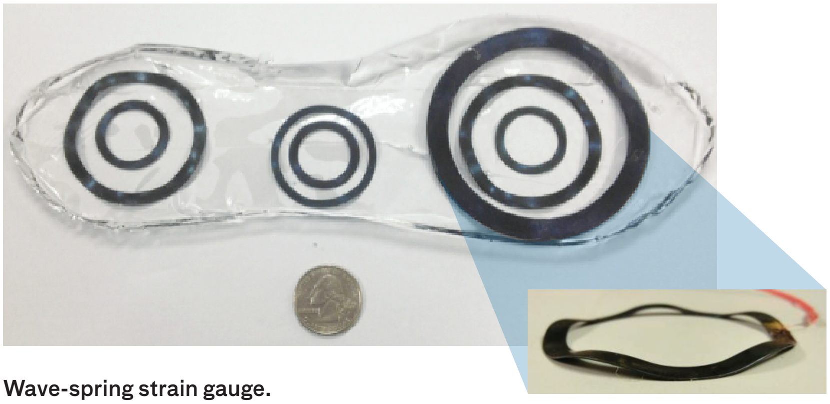


The measurement of an individual foot (signal coming from the capacitive insole) shows (1) the impact force on the heel, (2) the weight over the entire foot, and (3) the push-off force of the ball of the foot. In this case, note the relative similarities of the push-off and the variations in the heel impact throughout the entire test period.



Load cells, positioned at three discrete points on the foot, are integrated into the midsole of a standard warfighter boot.

While force-sensitive treadmills (the "gold standard to measure pressure on the joints," according to Lacirignola) and motion-capturing cameras are very accurate, they lack practicality beyond laboratory settings. "Taking measurements like running up a hill and going up stairs outside of the lab has never been done outside of a lab before," Lacirignola continues. Without compromising natural gait rhythms, the load-sensor suite technologies can assess how envi-



Wave-spring strain gauge.

But if there were a way to quantify how much load, or weight, a soldier is carrying, and characterize the network of motions and forces that are involved, could injuries be prevented?

ronmental factors, such as uneven terrain, impact locomotive patterns and injury susceptibility.

However, the force-sensitive treadmill will be useful in evaluating the accuracy of the sensor technologies (i.e., a calibration tool). Currently, a USARIEM-Lincoln Laboratory study is comparing the results obtained from the treadmill to those from the load-cell instrumented boot. The accuracy of the wave-washer and wave-spring designs will similarly be tested after the designs are further developed and new data are collected over the next few months. The team continues to assess the effectiveness of the capacitive load sensor, too.

Wave-washer strain gauge insert (wave washer in inset).

Besides these studies, current objectives include miniaturization and seamless integration of the electronics into the sensor systems, with an eye toward wireless data transmission. The team will also be conducting a cost-benefit analysis of price versus durability in the context of mass production (individual production costs for the prototypes range from $20 to $3500 a pair). Once the technology is fine-tuned, it could be adapted for use in sports medicine, athletic performance training, weight and exercise monitoring, and occupational safety compliance. Hughes thinks that a similar technology could also be used to "detect load on soldiers' backs and shoulders, or even to assess helmet blast force."

BIOMEDICAL DEVICES

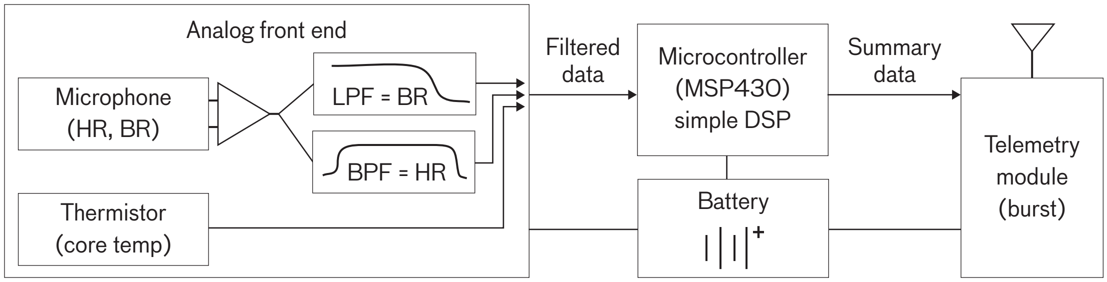
Ingestible Biosensors

An electronic "pill" could optimize physiological status monitoring

Daytime summer temperatures in Iraq and Afghanistan easily soar into the triple digits. Troops stationed in such hostile environments face a dry, desert-like climate, all the while lugging around heavy gear and equipment. Not surprisingly, they are at a high risk for heat exhaustion, heat stroke, and serious heat-induced complications, such as liver damage and kidney failure.

Knowing a soldier's core temperature—as well as heart rate and breathing rate—can lead not only to risk mitigation and preventive medicine, but also to operational performance enhancement and post-combat injury monitoring. Physiological status monitoring (PSM) systems, such as heart rate chest straps and ingestible core temperature pills, are already on the market; however, these devices suffer from limited operational utility because of uncomfortable design elements, insufficient battery life, poor signal reliability during an individual's movement, and inability to measure multiple physiological parameters at once and with a single device.

The U.S. Army Research Institute of Environmental Medicine (USARIEM) is constantly seeking better ways to monitor human physiology, according to Albert

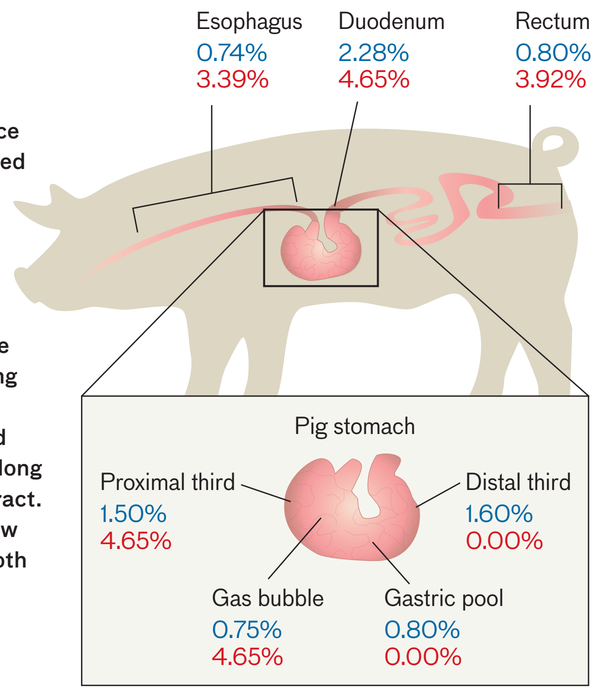


Schematic of an ingestible electronic device that concurrently measures heart rate (HR), breathing rate (BR), and core temperature (CT). Acoustic signals recorded from the microphone are fed through a low-pass filter (LPF) and band-pass filter (BPF) and then sent to a microcontroller that performs simple digital-signal processing (DSP) to determine HR and BR.

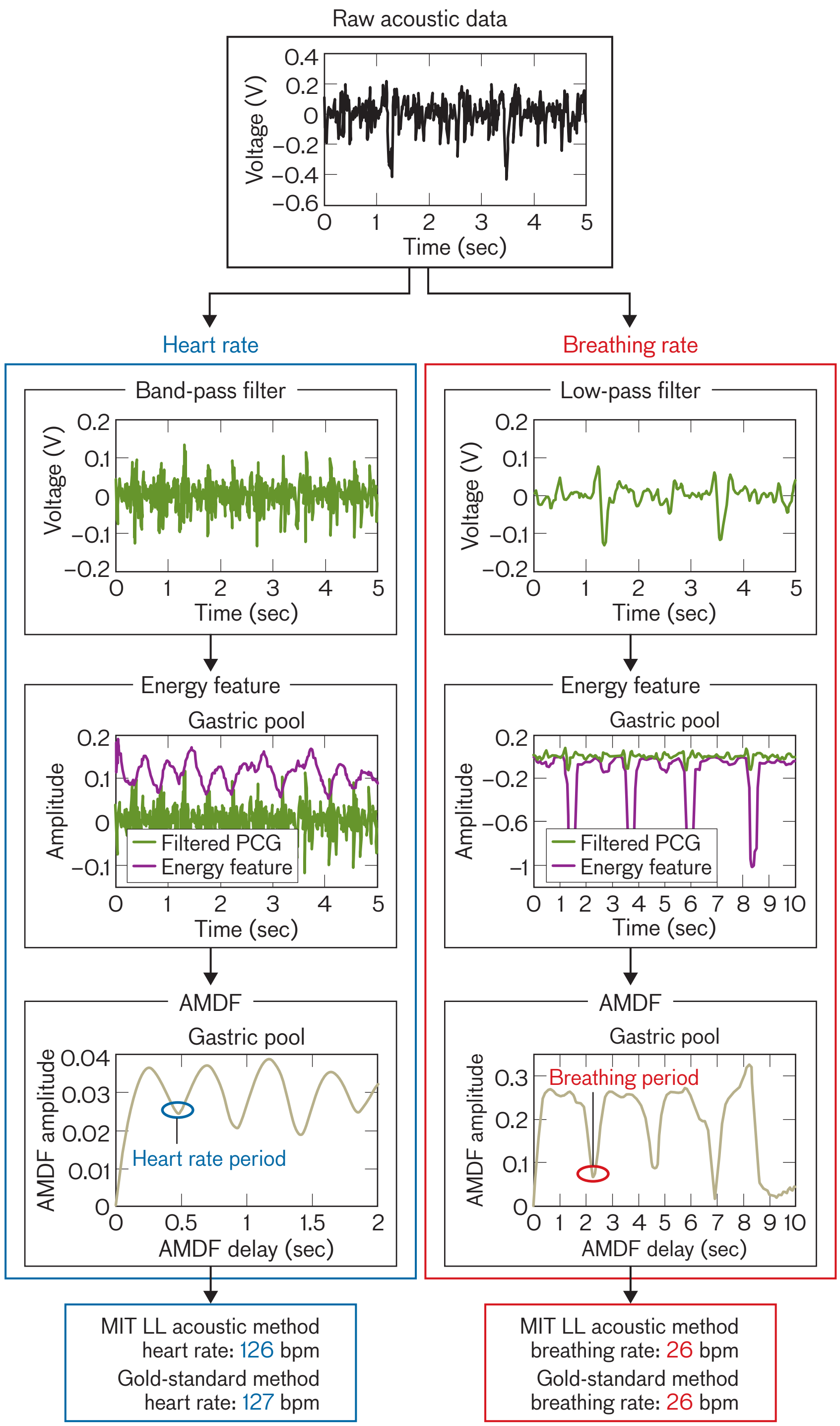
Swiston, a biomaterials scientist in the Bioengineering Systems and Technologies Group at Lincoln Laboratory. Swiston, along with fellow group members Tadd Hughes and Gregory Ciccarelli, and MIT collaborators Giovanni Traverso and Professor Robert Langer (Department of Chemical Engineering), are working toward this USARIEM goal. Together, they have been developing a single ingestible device capable of simultaneously measuring core temperature, heart rate, and breathing rate.

The device will feature two sensors: a thermistor and a microphone. The thermistor senses temperature variations based on changes in electrical resistance. The microphone, or "digital stethoscope" as Swiston describes it, is sensitive to the frequencies of acoustic signals from the heart and lungs. Typically, these cardiac and respiratory vibrations are converted into a graphical representation known as a phonocardiogram. In this device, however, signals will be fed through an amplifier and a series of analog filters. These filtered data will then be sent to a microcontroller that performs simple digital-signal processing to determine heart rate and breathing rate.

The percentage difference between externally derived HR and BR data using gold-standard methods and internally derived HR and BR data from a phonocardiogram/average magnitude difference function signal processing analysis as recorded by an endoscopically guided microphone at all sites along a pig's gastrointestinal tract. For each site, note the low percent error rates for both HR (blue) and BR (red).



So far, the system has only been modeled on pigs. With an almost identical gastrointestinal (GI) tract, equivalent heart and lung sizes, and similar body weight to a full-grown human, a pig closely mimics human physiology. To test the system, an endoscope (a tubular internal viewing instrument) guided a microphone through every point along a pig's GI tract, where acoustic data were recorded. External vital signs were also taken to compare to the acoustic data derived from the team's internal microphone-based method. The results show a high degree of accuracy between the datasets for both heart rate and breathing rate. (This model did not test the thermistor component of the system because thermistors are already widely accepted to



Signal processing flow for determining HR and BR in beats per minute (bpm) using MIT Lincoln Laboratory (MIT LL) acoustic method, where PCG stands for phonocardiogram and AMDF is the average magnitude difference function used to calculate HR and BR. Raw acoustic data derived from internal microphone sensor are fed into filters to remove noise. The filtered data are then sent to a microcontroller that performs simple digital-signal processing. HR and BR using gold-standard methods (an electrocardiogram for HR and a capnogram for BR) are included as a frame of reference.

be one of the most accurate types of temperature sensors.)

Swiston says the team "would really like to get to the point of having the pig swallow a device." With current commercial components, the team estimates the first prototype will be 2 cm in length and 1 cm in diameter, but the team is confident that the device can be further reduced in size to facilitate ingestion. "This device *will be* smaller than many vitamins people voluntarily take on a daily basis," comments Swiston.

According to Swiston, the team is on the "cusp of building an actual product" with unit parts estimated to be under $10. The device will need to be made of a material resistant to acid, perhaps a polycarbonate sheathing. "This decision will be made later when we know exactly how big the electronics are," Swiston continues. Another decision will involve power consumption, a requirement that will depend on whether the device is intended to be persistent (affixed in the GI tract for some extended period of time) or transient (naturally passed through the GI tract). This consideration is part of a larger concept-of-operations assessment that will need to evaluate several questions:

- *What does the user want to know?* Does the user want to know heart rate, breathing rate, and core temperature all at once? Does the user only want to know breathing rate? Or does the user want to know a different vital sign altogether?
- *For how long does the user need to know this information?* Is the user monitoring physiology over

the long term or in emergency situations? How frequently do vital signs need to be updated and reported?

- *Can the person ingesting the device tolerate it?* Would GI-related complications or other medical conditions inhibit the proper functioning of the device?

For now, the team will focus on building a transient, ingestible PSM pill that can last up to 24 hours and simultaneously measure heart rate, breathing rate, and core temperature.

The finalized device will have broad applicability not only in warfighter health and performance but also in sports and medicine. "Performance athletes want to know their heart and breathing rates with high fidelity," Swiston notes. "Marathon runners or National Football League players can swallow the pill right before a race or game or training practice." Swiston continues, "This device would also be great for burn victims. Measuring their vital signs is extremely important, but putting electrocardiogram (ECG) electrodes on their already fragile skin is, of course, unpleasant." Other applications of the device include triaging patients in the emergency room, monitoring the live-at-home elderly, warning surgical patients of complications like postoperative fever, and detecting cardiac murmurs and asthma, for instance.

Swiston envisions the device will eventually be able to measure other important physiological parameters, such as the saturation of oxygen in the blood and pH levels. He also foresees the evolution of an "ingestible modular device with individually 'prescribed' components most appropriate for a patient's medical condition" to address the different needs of military and civilian users. Another possibility involves using a persistent PSM pill as a drug-delivery mechanism that would be induced by specific changes in an individual's physiological status. A similar system may be useful for delivering powerfully therapeutic bacteria, particularly anaerobic bacteria (bacteria that live and grow only in the absence of oxygen), directly into the GI tract.

Are ingestible electronics the wave of the future? Swiston thinks it is a matter of redefining our cultural norms: "At first, swallowing electronics may be just as novel as brushing your teeth once was. But, who knows, one day we could be swallowing these devices every day!" With the expanding field of ingestible electronics—backed by the now decade-long Food and Drug Administration approval of their clinical use—this idea may be an easy pill to swallow after all.

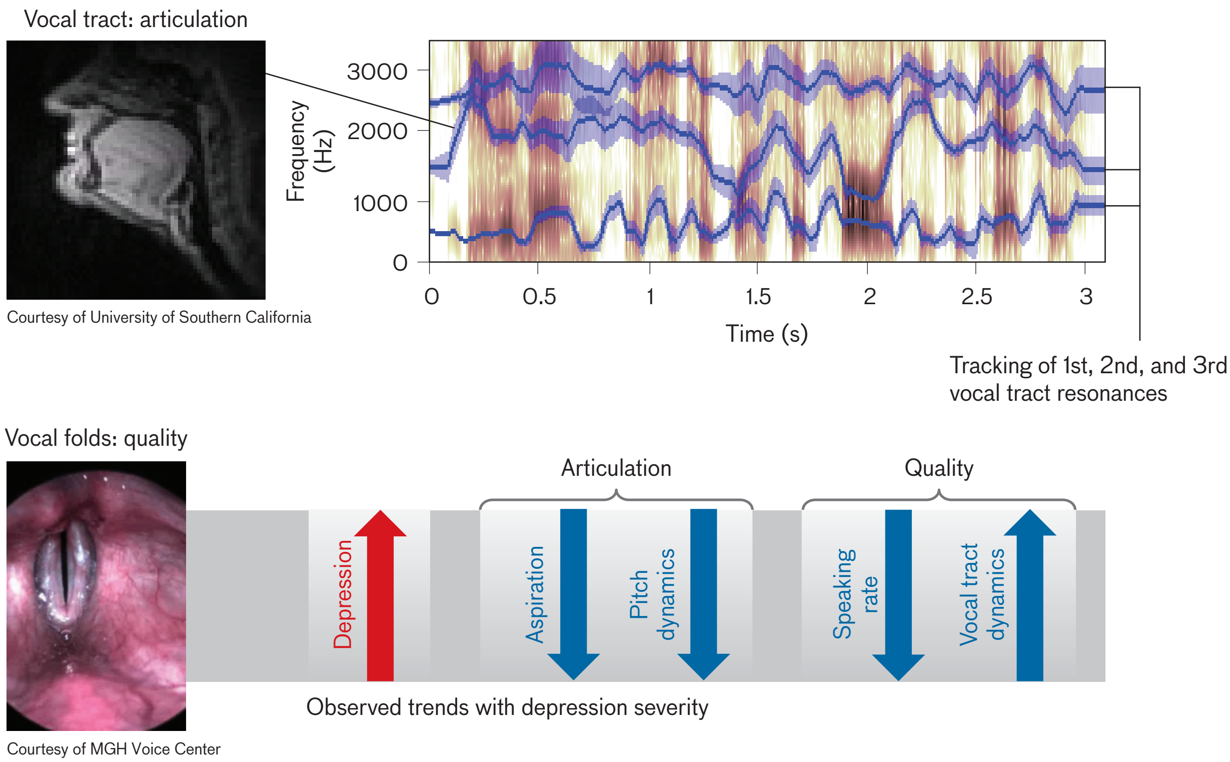
SPEECH TECHNOLOGY

Beyond What the Words Say

Vocal features may predict the severity of depressive disorders

The television ad for medication to treat depressive disorders tells us, "Depression hurts." While the ad refers to the physical and emotional pain endured by individuals, recent news articles remind us that depression also hurts society. According to an AtWork posting in October 2013, a Gallup survey conducted on data collected in 2001 and 2012 concluded that America's businesses face an annual $23 billion loss of productivity caused by employees' depression-related health problems. The National Alliance on Mental Illness reports that compared to people without depressive conditions, individuals experiencing depression are more apt to abuse alcohol and drugs, are more prone to chronic illnesses such as diabetes or heart disease, and, most sadly, are more at risk for committing suicide. A May 2013 article in the *New York Times* reveals that the suicide rate for Americans aged 35 to 64 has increased 30% from 1999 to 2010. Every 65 minutes, a military veteran commits suicide, and suicides among active-duty military personnel reached an all-time high in 2012, reports *Forbes* magazine. The costs exacted by depression are great: the personal anguish and dysfunction experienced by the sufferers and those close to them; organizational and financial burdens shouldered by health-care, military, and business enterprises; and tragic losses borne by those close to suicide victims.

Both civilian organizations and the military are very interested in methods that may alert doctors to a patient's early-stage symptoms of major depression disorder (MDD) so that intervention can be started before the condition worsens. To that end, researchers in the Bioengineering Systems and Technologies Group are applying Lincoln Laboratory's expertise in speech and language



The vocal biomarkers used in Lincoln Laboratory's study are based on articulation and quality of voice. Articulation is associated with vocal tract dynamics and precise coordination, while quality is dependent on vocal-fold vibration regularity.

processing to the identification of physiological indicators of MDD. They have had promising results from investigations into phonological and articulatory characteristics of speech that may indicate the severity of a person's depressive state. "We are looking at the correlation between depression severity and certain vocal biomarkers," says Thomas Quatieri, a senior staff member in the group. "Some of the vocal features we have considered reflect articulation and quality of voice. These include coordination of precisely timed vocal articulators, average speaking rate, individual phoneme speaking rate, pitch and energy dynamics, and irregularities in vocal-fold vibration. These characteristics are often perceived as slowness, slur, monotony, breathiness, and hoarseness in the depressed voice, but may be 'silent' and only be detected by advanced temporal-spectral analysis."

Traditionally, mental health professionals have diagnosed MDD by evaluating patients on scoring systems that rely on qualitative indicators such as a patient's insomnia, sudden weight gain or loss, agitated state, and self-reported feelings of ennui and guilt. Two commonly used scoring tools are the Hamilton Rating Scale for Depression (HAM-D), which looks at 17 different symptoms, and the self-reported Quick Inventory of Depressive Symptomatology (QIDS), which gauges 16 factors. The Laboratory's vocal biomarker approach could provide clinicians with a quantitative, more objective tool to supplement the interview-based HAM-D or QIDS diagnostic methods. In addition, detection of speech characteristics associated with depression may enable earlier and more uniform diagnoses than use of the HAM-D or QIDS techniques alone and may also be useful in automatic monitoring of treatment or relapse after treatment has ceased.

"The research on voice to detect depression severity has been going very well," says Quatieri. "We have focused our investigation on a set of parameters that includes the physiological aspects of creating speech." Applying signal processing techniques to recorded samples of freely spoken and read speech, the research team has developed two innovative vocal biomarkers based on (1) phoneme-dependent speaking rate and (2) incoordination of vocal tract articulators. This focus was motivated by the clinicians' observation that people with depressive conditions exhibit psychomotor impairment, manifested by slow thinking, sluggish and uncoordinated physical movements, and listless emotional reactions. "For the phonological class of biomarkers, our team has examined durations for specific language phonemes (sound units such as for a vowel or a consonant) and for pauses," says team member Bea Yu. The signal patterns when compared to baseline data from non-depressed subjects show that speech produced by depressed individuals exhibits differences in phoneme and pause durations. Identification of subjects' level of depression from their speech samples correlated well with the assessments of these subjects made by clinicians using the HAM-D assessment metric.

The Laboratory team is also looking at speech patterns that may indicate a lack of coordination of the vocal articulators (tongue, jaw, larynx, vocal fold, lips). By measuring the cross-correlation in vocal tract resonant frequencies seen in samples of recorded speech at different time scales, the researchers may have an indirect measure of how well the vocal articulators are moving together. Changes in resonant cross-correlation may be due to uncoordinated dynamics of speech production, such as with dispersed timing and phasing of articulators, and may indicate depression. "The more highly depressed a person is, the greater the decline in coordination. This incoordination measure of vocal articulators has provided our team with high correlation gains against the HAM-D assessment metric," says James Williamson, a technical staff member in the Bioengineering Systems and Technologies Group.

> The Laboratory's vocal biomarker approach could provide clinicians with a quantitative, more objective tool to supplement interview-based diagnostic methods.

The team has seen that their correlations between vocal biomarkers and heightened depressive states are in line with the determinations of depression severity made by clinicians using the HAM-D and QIDS methodologies. Interestingly, quite often the biomarkers correlated more strongly with a single criterion of the two scales—for example, psychomotor retardation—than with a total score from a person's evaluation. "This may lead to predictors of depression state that use biomarkers tuned to individual subsymptoms of depression," says team member Brian Helfer.

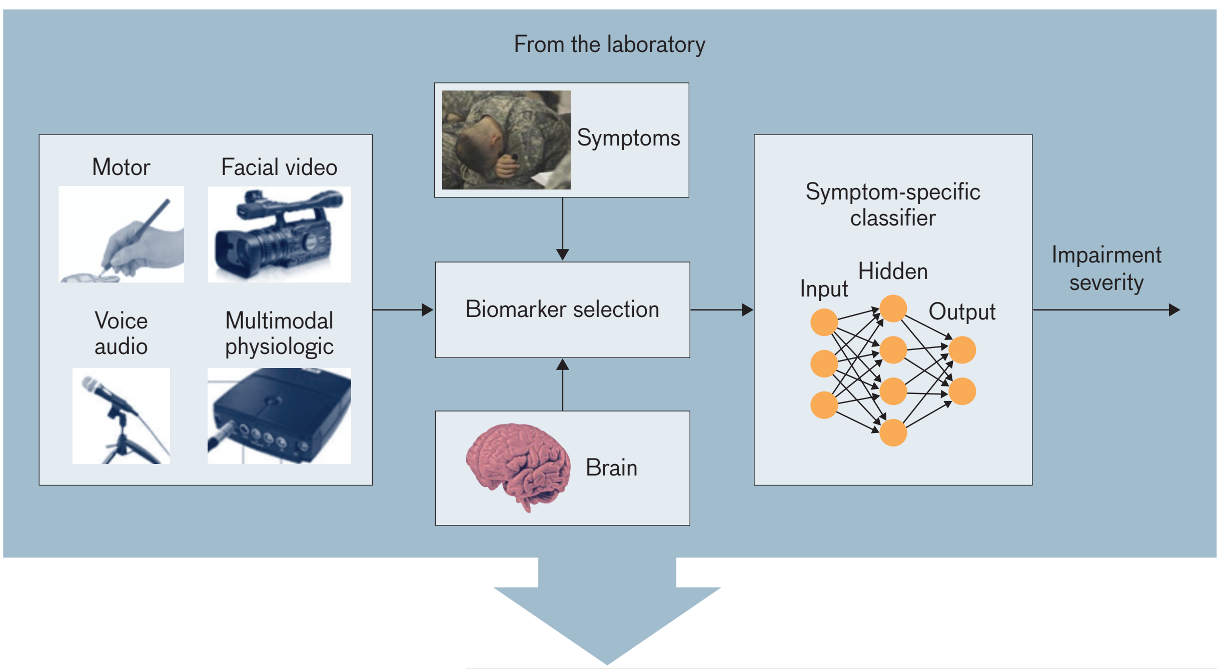
In October, a Lincoln Laboratory team was awarded first place in the Audio/Visual Emotion Challenge and Workshop (AVEC 2013) event. The challenge was to exploit audio and/or video information to estimate the depression severity of people diagnosed with MDD. In spring 2013, participating research teams were given a set of audio/video recording sessions of patients and were tasked to predict patients' scores on a clinical depression assessment (Beck Depression Inventory) on the basis of objective biomarkers derived from the recorded speech samples or videotaped facial features. The Lincoln Laboratory team used only the speech data, applying its techniques in assessing phoneme-dependent speaking rate and lack of coordination of the vocal tract articulators. Although the AVEC datasets were in German and the Laboratory's work has been only on English-language data, the Laboratory's biomarkers performed well. The team's predictions highly correlated to the Beck scores, earning their technology a "victorious" rating by a large margin.

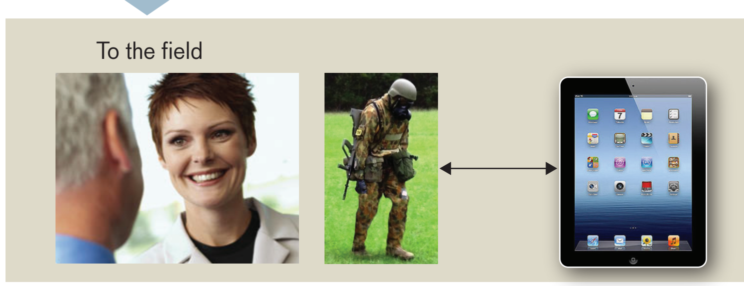
The Lincoln Laboratory team consisted of Quatieri, Williamson, and Helfer, technical staff members in the Bioengineering Systems and Technologies Group, Daryush Mehta, a consultant to that group, Yu of the Intelligence and Decision Technologies Group, and MIT graduate student Rachelle Horwitz. "Our depression team is highly interdisciplinary, representing skills in signal processing, machine learning, speech science, psychology, and neuroscience—a mix that is essential in addressing the complexity of human depression," says Quatieri. The team also acknowledges Nicolas Malyska, a staff member in the Human Language Technology Group, and Andrea Trevino, a former summer intern and currently a University of Illinois graduate student, for their involvement in early work on phoneme-dependent speaking rate.

Quatieri says that the work on vocal cues to depression is becoming part of a larger multimodal approach to determining depressive states via physiological indicators.

In collaboration with doctors and researchers from Massachusetts General Hospital and the Wyss Institute for Biologically Inspired Engineering, Lincoln Laboratory researchers are studying how the muscle movements behind facial expressions may be indicative of MDD and what changes in autonomous physical functions, such as heart rate and skin conductance, are symptomatic of MDD. An analysis combining results from this variety of quantifiable factors with biomarkers tuned to individual symptoms of depression could add scientific measures to the art of diagnosing depression. “This research may also have implications beyond depression,” says Quatieri, “for example, in diagnosing traumatic brain injury, post-traumatic stress disorders, early dementia, or amyotrophic lateral sclerosis (ALS, also known as Lou Gehrig’s disease), or even in assessing cognitive overload or stress.”

“Our team is quite pleased with our progress and in particular our first-place standing in the recent international depression challenge,” says Quatieri. “We view this win as a research step toward helping our soldiers and veterans, as well as civilians, who are suffering from particularly high depression and suicide rates. We envision, for example, mobile devices for use in automatic monitoring of the effectiveness of treatment or for early intervention and relapse.”





A multimodal technological approach may dramatically change the way, and how rapidly, depressive disorders or neurological impairment is diagnosed and treated. The future vision includes a mobile technology assistant that would bring lab results to clinicians in the field.

VISUAL ANALYTICS

It’s All in the Design

An exercise in visual analytics informs the approach for developing future usable network-monitoring interfaces

Imagine you are presented with the following scenario: A fictitious company (“Big Enterprise”) has hired you to create a single, integrated graphic display design that provides network operators with situational awareness of their global network. The operators are responsible for maintaining various company services—cloud storage, streaming media, video teleconferencing, and voice-over-Internet protocol—by managing network-related issues ranging from malware threats to bandwidth allocation. Big Enterprise's current display of multiple computer screens is difficult to understand and does not clearly show how events interrelate. The company is seeking a user-friendly design that will enable operators to balance the health, security, and performance of the network. To do so, operators will need an architecture that supports many facets of network management:

- Maintaining a clear and accurate picture of the entire network
- Detecting changes in network activity and understanding their operational impact
- Responding to issues with the best course of action
- Tracking the progress of issues as they are being identified, prioritized, and resolved

This scenario was presented in the 2013 Visual Analytics Science and Technology (VAST) "Situation Awareness Display Design" mini-challenge. A multidivisional Lincoln Laboratory team responded to the challenge, earning an honorable mention for their design's visualization of event relationships. Diane Staheli, team lead and visualization and user interface/user experience (UI/UX) engineer in the Cyber Systems and Operations Group, attributes the design's success to the team's diverse composition. "We were able to consider the challenge from many unique perspectives,"

> A system can have the fastest and most accurate algorithms, but if end users can't intuitively work with the results, it's difficult to label the system a success.

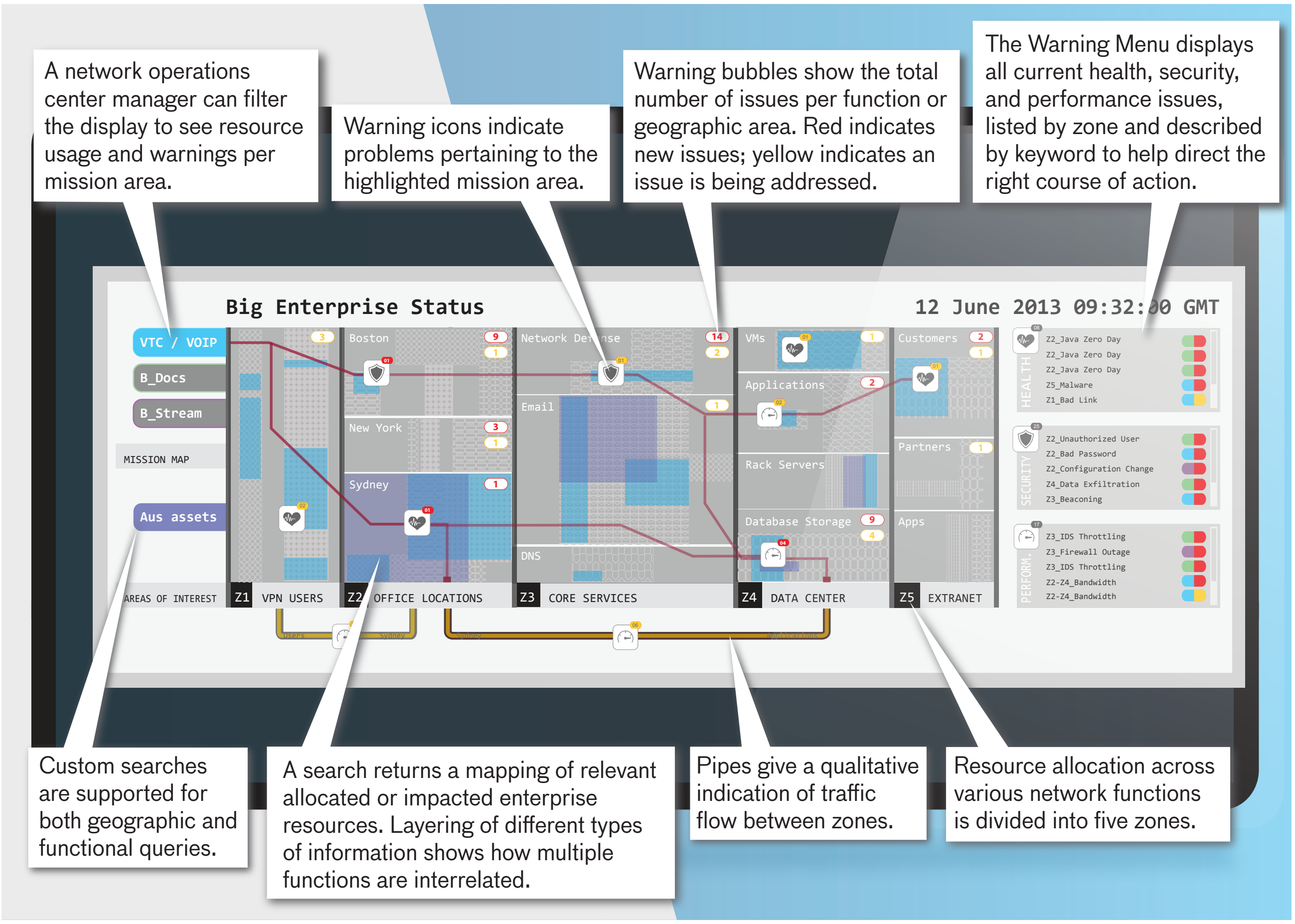
she explains. The team consisted of domain experts (analysts and network operators), visual designers, and human-computer interaction experts. With this multidisciplinary team in mind, Jeffrey Gottschalk, associate leader of the Cyber Systems and Operations Group, describes the VAST mini-challenge as a "perfect fit" that "combined human-centric design skills with real-world insights from analysts."

Staheli also credits the strength of the design to the team's approaching the challenge from an end-user perspective: "We considered what was required for a real network control center on the basis of the team's deep experience with network operations centers and worked from there. To focus our design efforts, we imagined that a natural disaster was happening and thought about how it may play out in the cyber world, envisioning what kind of decisions the network manager would need to make. Then, we scripted a scenario to use as a working document." Teammate Michael Snyder, a software engineer and UI/UX designer in the Intelligence and Decision Technologies Group, explains why the team chose to create this realistic scenario: "The challenge gave us no data to work with, so we had to construct the data ourselves." He continues, "Because of this [lack of data], the mini-challenge was actually more challenging than our work at the Lab."

Providing a holistic view of network operations, the final design displays which kinds of information and problems are important to network operators, how problems overlap and interact, and how problems impact a particular company service. This information is communicated through a multilayered, color-coded, icon-based display that enables operators to simultaneously view a variety of information to gain and maintain situational awareness.

The display divides the network into five zones to portray connectivity needs and network users for each company service ("mission area"). "Pipes" show traffic flow between zones, while overlapping of network assets shows how resources are allocated and interconnected. Color-coded warning bubbles reveal the total number of problems per function or geographic area and problem resolution-status. Heart, shield, and clock symbols are featured throughout the display to alert operators of issues relating to the health, security, and performance of the network. A warning menu features color-coded pill icons indicating which mission areas are most affected and whether or not the issue is being addressed. Operators can switch display views to see network warnings and resource usage in each mission area.

How can this exercise in visual analytics be useful? According to Staheli, the challenge was a "good opportunity to think about a problem creatively without the constraints of writing a realistic



Annotated display of computer network operations explains design functionalities that facilitate situational awareness. By consulting the Warning Menu on the right-hand panel, a network operator will note, for example, that in Zone 1, there is a bad link (color-coded in blue) that is being addressed (yellow).

algorithm or implementing a functional system." This type of creative thinking can then be applied when a concept needs to be realized in an operational context. "Is this design concept something we can execute by using data that are already available at the Lab?" Staheli wonders. Maureen Hunter, a network traffic analyst in the Laboratory's Cyber Systems and Operations Group, says she would definitely use the display operationally: "Our design fuses together information that you typically would get only by consulting five to ten different sources. It combines the best of multiple monitors to provide one visual area."

This exercise relates to other cyber work, such as the Lincoln Laboratory Cyber Situational Awareness program, which provides a platform for network defenders to monitor network activity, as well as projects involving UI/UX design and text analytics. Alongside feedback from pilots and image analysts, Snyder is also developing a quick-reaction-capability (QRC) program that provides an intuitive interface for ground situational awareness. Thinking of this project and the mini-challenge, he emphasizes the importance of usability and visualization: "A system can have the fastest and most accurate algorithms, but if end users can't intuitively work with the results, it's difficult to label the system a success." Similar to the mini-challenge display, the QRC program features colors and icons, design elements that highlight essential information to help end users view flight paths and plan missions. For Snyder, the challenge also brings to mind how visual analytics has parallels to text analytics, as built into document-searching software like Structured Knowledge Space, a military intelligence reporting search and discovery system: "Different branches of the military need to mine through hundreds of thousands of report documents, a task that may be aided by visual display tools that make data more manageable. For instance, documents could be shown as pins on a map to geographically indicate where they originated." Hunter also sees the value of visual display tools in working with histograms, graphs, and other visualizations to detect network traffic anomalies.

There is certainly a desire for more usable interfaces, as evidenced by an increased demand from sponsors. "With military personnel facing assignment changes every two years, they need software that does not require extensive training" to ease the learning period that comes with each transition, Staheli explains. Snyder adds that some sort of standardized visualization framework would be helpful because personnel who shift locations often have to learn new tools while disregarding the tools they learned in previous deployments. In particular, Combatant Commands have been asking for an integrated display operating on a single system instead of multiple systems at once. "The situational awareness challenge helps inform our [Lincoln Laboratory's] thinking in how we would approach this kind of request," says Staheli. Hunter says that network analysts can use these types of interfaces to acquire network intelligence that would inform decision makers about areas of foreign interest and attempts to compromise data.

The exercise also highlighted some of the challenges associated with information visualization, a field that Snyder believes is growing

Data visualization also becomes difficult when users do not know what is in the data at hand or what they need from the data.

increasingly more important. For one, advances in screen resolution and size (think HDTV resolution and billboard-sized screens) are "great for end users but problematic for designers who have to accommodate more information in a single view and in greater detail," explains Snyder. In fact, Snyder mentions that the team experienced this problem of "clutter" while designing their mini-challenge display and had to come up with a way to reduce but not remove the information. At the other extreme, advances in wearable mobile interface technologies, such as Internet-enabled wristwatches and Google Glass, have considerably smaller displays that will "require interaction designers to think about how visualization may be utilized beyond the form factor of the browser," says Staheli.

A larger challenge is that of data management. One of the major concerns is being able to navigate through the wealth of data, such as that arising from social media. Analysts need to easily consolidate and sift through Internet forums, blogs, social networks, photograph-sharing sites, and other social media outlets in order to find terrorist networks, for instance. Even in looking at one social platform at a time, there are issues. "When following Twitter for cyber threat events, analysts see Twitter messages that stream separately from their other real-time graph displays. This separation means that analysts must consider whether a Twitter message relates to other live activity sensors," Hunter explains. Another challenge is that data are rarely in the same format, making integration of information from various sources into a single platform difficult, especially when restrictions such as access controls and firewalls are encountered. Data visualization also becomes difficult when users do not know what is in the data at hand or what they need from the data. "It's like working with a blank canvas," says Snyder.

At a more basic level, many different approaches to visual analytics are available. "Some users may prefer to see all available information at a glance, other users may want a customized view specific to their needs, and yet others may seek an interactive experience," Staheli explains. Snyder thinks a display that allows users to switch between different views and "hide" less relevant information may help avoid alienating users who are accustomed to a certain approach. Nonetheless, he agrees that this split in visual analytics is a tough act to balance: "Oftentimes, users may have one vision in mind, but they overlook the problems associated with that vision or fail to realize that multiple display options exist. Yes, there are bad 'answers,' but no, there is not one right 'answer.'"

Despite these differences in opinion, one point is agreed upon: *it's all in the design.*