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Universal Drilling Language for Improved Safety and Efficiency in Geothermal Drilling Operations

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ABSTRACT

Communication in the drilling industry needs a great deal of improvement. Currently, the vocabulary exists on a continuum from nonexistent or very broken to sometimes only moderately effective. Thus, a precise and unifying drilling language will unlock the safest and most efficient operational flows ever seen. Improved communications will simultaneously eliminate the many human errors induced by the misinterpretation of words and phrases. Most importantly, this paper identifies the geothermal drilling sector as the best candidate for adopting such a revolutionary framework and seeing the most immediate impact. There is a need for a new form of training, and our research and training concepts help fill that gap.

When it comes to the current drilling revolution, our human drillers are on the quieter side, while technology, data, and algorithms are busy making all the headlines. But this is no surprise – our modern culture lives and breathes digitally. Industry innovation has primarily come from technical improvements in the last few decades, so we propose that “human-in-the-loop” simulation training will be a fundamental next step for the industry’s future success. Our research begins to bring the human back together with the machines. Secondly, we propose that a streamlined language package will shorten the learning curve for future verbal-computer interactions and machine-based task interpretation. Ultimately, our language training will improve the rig floor’s communication, safety, and overall efficiency while enabling the first-ever interface to the “human-machine” drilling system axis.

This paper presents two novel training methodologies that prioritize human abilities (and limitations) over the technical requirements for drilling. Research participants drill in simulated scenarios while being observed for their communication skills and cognitive abilities. The first experiment deals with communication phrases, and early results suggest that language precision might significantly impact task completion time and rate. The second experiment in our series shines the light on our drillers’ cognitive ability to focus. We find that the ability to control (or mitigate) attentional leaks has a sizeable effect on drilling outcomes. Together, these measurable human factor approaches provide the first practical steps we can take. The potential for improving our geothermal drillers’ safety and performance is significant and needs further explanation.

1. INTRODUCTION

Our “human-in-the-loop” training concept aims to improve performance by placing humans directly into realistic drilling situations and iterating their interactions. Instead of chasing technical innovation, this training concept places the human at the center of the experiment, and this is how we can more effectively fine-tune our drilling behaviors. The benefits will extend far beyond simulated environments. Once fully adopted, these concepts will impact the office, field, user interfaces, training modules, and so much more. A standardized communication framework will become the essential glue between humans and machines. A universal language will become necessary for the next generation of engineers to work safer and more efficiently, especially in remote operations or rapidly-evolving applications. One of these applications, geothermal, shows extreme promise for the world’s future energy needs. Therefore, the long-term viability of geothermal drilling underscores the necessity for earlier and widespread adoption of a drilling language, “human-in-the-loop” training, and the other concepts found in our experimental series. Furthermore, Bavadiya et al. (2019) have shown that geothermal drilling training may require some specific training features which are not in common with existing oil and gas drilling. The primary outcome of the paper was that slower ROP in geothermal activities affects complacency and reduces situational awareness.

The central concept proposed in this paper, the Universal Drilling Language (UDL), emphasizes the need to communicate commands, requests, affirmations, and more with precision *and* accuracy for a wide range of field personnel with various backgrounds. Concise language considers what is necessary, excludes the extraneous, and communicates it clearly – leaving no room for misinterpretation. The experimental and training process for improving language requires three stages: observing trainees’ intuitive phrases, inserting some “imperfect” phrases, and finally iterating to “perfect” speech.

Our first experiment pairs research participants and assigns each into one of two roles: Driller or Assistant Driller. The Driller handles the simulator controls while the Assistant Driller verbalizes a string of drilling parameter changes. The researcher measures performance via time to drilling task completion, rate of drilling task completion, and a host of subjective errors. There are three distinct communication phases (Natural, Imperfect, and Perfect). While the drilling industry’s existing intuitive vocabulary might not be inherently wrong, we hypothesize that it still leaves too much room for interpretation. We expect our “Imperfect” phase to cause the participants’ performances to suffer drastically but ultimately help craft the “Perfect” phrases. These phrases yield the most consistent, fastest, and safest results. IT is continuous feedback from each participant group that leads to the beginning of our goal: a framework to build drilling's own language. Altogether, the UDL concept will ensure that the geothermal drilling sector progresses via human improvements (as well as technical), to create a safer and more efficient working environment.

The second experiment involves human psychology to a much greater extent. Cognitive psychology concerns itself with the science of the mind and includes domains like perception, memory, knowledge, thinking, and beyond. Of particular interest for the direction of this experimental series is the scope of attention. More specifically, our study includes subtopics such as dichotic listening and verbal shadowing. Human psychology and drilling technology do not have to be at odds. Instead, our research intends to explore their compatibilities. Cognitive psychology is pervasive – it impacts all drilling activities and processes requiring any degree of human involvement. Our experiment tests a single participant's ability to focus their attention "in the drillshack" while competing stimuli are present. Most impressively, a specific cognitive technique (verbal shadowing) is used as the intervention and found to have a measurable improvement for drilling performance. Since the geothermal drilling process is one in which the human demands are as extreme as its risks, it is prudent to use all available techniques for efficient and safe performance.

2. BACKGROUND

To understand how the human and machine extremes are compatible, it takes a considerable amount of background knowledge to test and effectively weave our human factor concepts into drilling's technical landscape. Background topics for the first experiment (known as the "Driller's Roadmap") include drilling simulators, non-productive time, and human factors safety. The second experiment ("Verbal Shadow Drilling Study") requires understanding topics such as cognitive attention, dichotic listening tests, and verbal shadowing.

2.1 Testing Communication Phrases

The first experiment in our human-focused series is the Driller's Roadmap (DRM) Language Experiment. The DRM's primary objective is to test and then improve human drilling performance by fine-tuning the spoken words and phrases. Using a drilling simulator, we create a repeatable and safe drilling environment. This constant enables the researchers to observe, test, and then modify the human factors "in-the-loop" of the experiment.

2.1.1 A Case for the Universal Drilling Language

Language standardization is not a new topic altogether. Other industries, such as aviation and medicine, have led the way. Specific aviation processes are already streamlined via communication protocols, leaving zero room for misinterpretation. As an oversimplified example, when the experienced Australian captain says "prepare for landing," the German copilot knows *exactly* what to do. The copilot deploys the landing gear and then follows with the subsequent (prescribed) steps and confirmation phrases. These two pilots might speak different native languages, be of different genders and ages, and routinely fly different aircraft. But, together, they can safely and efficiently get their cargo and passengers to the intended target. Is this a reality for modern drilling teams? What if the shale drillers of America were sent to work with the geothermal drilling teams in Germany? Can they at least communicate the basic commands on the drill floor? Would the management teams in the office be able to communicate pre-section requirements effectively? Probably not… yet. A "Universal Drilling Language" would enable our hard-working people to reduce non-productive time while minimizing lost-time incidents. But how can we develop the UDL and train our personnel? Drilling simulators.

2.1.2 Non-Productive Time

Time is money, and successful businesses must break even. But to really thrive, a business must charge more, perform more work in the same amount of time, or perform the same work in less time. With more effective communication, businesses can accomplish all three. Communication research is essential because it helps decrease human error while simultaneously improving process quality. And a higher-quality process usually results in a higher-quality result with less lost time. While the exact definition of non-productive time (NPT) can vary based on the application or goal, there is universal agreement that NPT negatively affects the bottom line. McKinsey & Company (2015) report that 70% to 80% of costs for offshore wells are time-related.

Furthermore, because the average cost of wells continues to rise (up 250% since 2007), *any* time-saving strategy needs consideration. Every 1% improvement matters, especially when compounded shift after shift, hitch after hitch. A commitment to tiny improvements consistently over time can produce significant results. Hardy (2020) also suggests that any individual, organization, or industry can reap magnificent rewards from seemingly irrelevant actions. This paper proposes that small and seemingly irrelevant improvements to communication will improve efficiency. Again, more work in the same or less time. It is commonly known that geothermal development is strongly affected by drilling costs, and thus any measures that reduce NPT are more than welcomed.

2.1.3 Human Error and Safety

While time and money are essential for business success, we cannot overlook the importance of human life. Safety is important because human life is sacred. We have loving partners, growing children, and wise, caring parents. There should only be one goal – zero losses from near-misses, minor incidents, unsafe acts, and major accidents. However, context is important. This paper cannot ignore the impact of safety culture, equipment failures, process design, and pure bad luck. However, it is understood that individual human action (or inaction) is a significant contributor to safety events on a rig. After a thorough investigation, the U.S. Chemical Safety Board (2016) concludes that communication gaps between the mudlogging crew and the Deepwater Horizon rig personnel contributed to the accident's severity.

2.2 Testing Attention

The second half of this experimental series involves even more cognitive psychology than the first. Everything we do, think, feel, or say stems from our foundational human capability known as cognition. Without exploring this “science of the mind,” optimizing the intersection between drilling humans and drilling machines remains impossible. One might think of computers and machinery as essential tools, but human cognition is the most necessary tool of all. Our human tools and abilities are required to accomplish every single one of the most excellent, challenging, and hazardous tasks known to man. Without cognition, we are left without the ability to create or invent our greatly needed drilling solutions. Without cognition, we are left without a lens to even perceive that a problem exists in the first place. Without cognition, we cannot even begin to theorize what engineering is. Our ability to thrive, work together, and build starts with the science of the mind.

2.2.1 Cognitive Demands of High-Risk Jobs

How we overcome the cognitive demands of our risky jobs and industries is a marvel and needs further exploring. Many commonly known and well-respected industries expose their workers to dangerous situations daily – construction, mining, logging, fishing, to list a few. From the individual to the organization, it is imperative to acknowledge the range of inputs that can lead to failure, harm, injury, or worse. Some risks are inherently physical, while many others can be mental, process-oriented, technological, etc. Collectively, these sets of risks and their subsequent consequences must come together. Tveiten and Schiefloe (2014) suggest developing risk images for high-risk integrated operations, especially when introducing new technologies. They define a risk image as the “combination of hazard identification and risk perception.” The most relevant high-risk sector for this research is geothermal drilling, which is growing in complexity and vulnerability. Risk images should not only be a part of the general framework for geothermal’s future, but human risk images, specifically, should be at the core.

Drilling operations require thousands of pounds of hydraulic pressure, millions of pounds of multidirectional force, risky working conditions, dangerous chemicals, among an abundance of many other risk factors. This collection of risks positions the drilling industry far within the high-risk category. Different tasks are associated with varying levels of personal and team risks, and any routine day on a drilling rig will undoubtedly include at least one high-risk scenario. Some tasks are singular and simple, while many others are more complex and require the repeated coordination of multiple people, thereby compounding the cognitive demands and risks. Furthermore, in geothermal drilling activities, attention may fade due to the slowness of the process and thus the possible loss of focus.

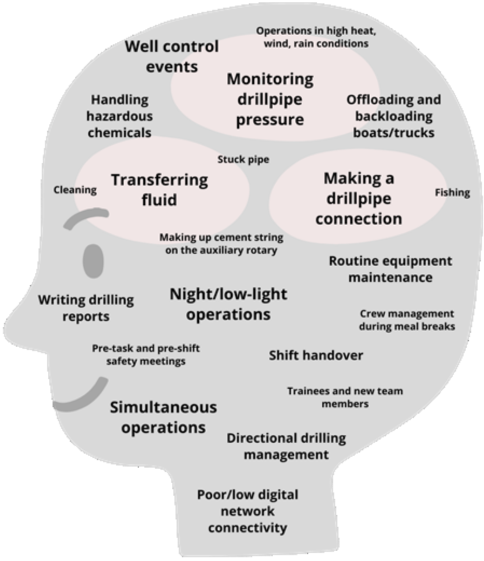

Figure 1: Routine drilling rig tasks involve some degree of cognitive energy

While not every drilling task requires the same level of cognitive function, even the simplest of tasks can and will ultimately accumulate a cognitive load throughout a shift. For example, Figure 1 provides a small sample size of activities that might occur on any regular drilling shift, and they all vary in cognitive demand and risk. While health, safety, and environment (HSE) have long been important to the drilling industry, continued research, training, and emphasis need to be placed on the forever-evolving complexities of human behavior. Instead of merely trying to protect humans via safety standards, the industry should embrace the more unknown interconnections between man and machine. Moreover, the drilling industry should be more proactive by striving to optimize human behavior, just as it optimizes its machine processes. If the geothermal drilling industry can learn to build drilling machines with human behavior in mind, then the entire industry will be able to flourish with dramatic improvements in HSE and productivity. The first human tool we will study is the cognitive ability of attention.

2.2.2 Attention as a Cognitive Tool

Humans are social creatures – we interact in groups to solve all sorts of problems for the greater good. Still, to interact effectively, humans must perceive and subsequently process vast amounts of inputs. All of these stimuli are continuously flooding the human sensory system. For example, let us consider this present moment. Sound waves are collecting on your outer ear, causing your eardrums to vibrate; your body is experiencing tactile pressures as it contacts the seat or floor beneath you; tastes and smells of your environment are marvelously uniting; and don't forget – you are effortlessly reading these words thanks to your visual system. The magic of this moment lies in your cognitive ability to focus attention when and where it is necessary. Imagine, for a moment, that you were incapable of "paying attention." It would take hours to accomplish a few simple tasks. Worse, you might miss out on essential features, lack personal safety, or be rendered completely ineffective as a productive human being.

For high-risk jobs like drilling, humans need to process many ideas, identify complex patterns, and experience far beyond the primary senses. Furthermore, crews of individuals must come together to accomplish complex tasks as safely and efficiently as possible. Luckily, the human brain has adapted to automatically filter and process most of the massive flood of sensory inputs. But exactly how much stimulus can our brains deal with?

The "information economy" and ongoing competition for human attention is still growing (Bohn and Short, 2012). In 1971, the American cognitive psychologist Hubert Simon was already proclaiming the need for organizations to better balance the human's limited attention with the overabundance of data flows. "A wealth of information creates a poverty of attention and a need to allocate that attention efficiently among the overabundance of information sources that might consume it" (Simon 1971). Attention shortening is now exacerbated as data-, information-, and machine-technology creep further into society, and (for our context) deeper into the drilling industry. So, a critical question needs exploring – how do we help our drilling teams pay more attention while their operational environments are growing with distraction? Again, the proposed UDL creates a communication framework that will naturally shift a human limitation (attention) into a procedural strength. It will help users to focus their attention through language.

2.2.3 Dichotic Listening Tests

One of cognitive psychology's enduring puzzles is figuring out how individuals can maintain their focus despite distracting inputs from nearby irrelevant tasks. For example, imagine you and some friends are attending a social function, and the entire room is buzzing with activity. How can you possibly focus on a conversation with a new acquaintance while your friends are right behind you, joking about last week's political shenanigans and football scores? This phenomenon has come to be known as the cocktail party effect. While it might seem trivially easy, it is entirely impossible without the cognitive ability of focused attention.

While the cocktail party effect might seem unremarkable to the average person, psychologists have deeply studied the phenomenon for many decades. Cognitive psychologists have drawn up the dichotic listening test – an experimental procedure for when an audio message plays into one ear and a second message into the opposite ear. Cherry's (1953) novel speech recognition experiments help us better understand the brain's potential for filtering out simultaneous, irrelevant, and unnecessary messages. During one of Cherry's dichotic listening experiments, he reports that subjects have zero difficulties tuning into one line of speech while "rejecting" the other. Interestingly, when the rejected line of speech switches from one language to another, the subject later reports that the language switch was neither registered nor intelligible. These dichotic listening tests help to prove that a human's attention can indeed act as a spotlight. The human brain can illuminate some stimuli while downgrading the priority of others.

When the desired stimulus happens to be a task-relevant command, it is imperative first to acknowledge it and act upon it. These observations reinforce our experimental goals – reproducing and studying the cocktail party effects within the drillshack will help us better mitigate human errors. Can our drilling teams focus their attention on what is most relevant when presented with distractions? This paper highlights the connection between attending to a command stimulus and accurately and efficiently carrying out a drilling task.

2.2.3 Verbal Shadows

A required part of a classical dichotic listening test is the verbal shadow. This technique is the intentional act of verbally repeating the stimulus from the attended channel (and is traditionally repeated verbatim) – the phrase comes into one ear, and the research participant repeats it word for word. By repeating the primary stream of speech from the attended channel, the participant focuses their attentional resources on the target stimulus, demonstrating that the phrases are recognized. Cherry (1953) reports, unfavorably, that as speech streams become more complex, much of the emotional and semantic underpinnings are lost due to shadowing. To be fair, the repeated streams in Cherry's original experiment were passages of random phrases linked together (and much longer than a few words). While a comprehension deficit is undesirable, the shadowing technique still proves that attention can be directed to separate concurrent speech streams. Most importantly, Cherry's research subjects do not report any significant processing from the unattended ear – except that sounds were heard.

While this verbal shadowing technique shows up in the literature, it also appears in practice. For example, pilots and air traffic controllers must shadow (known as "readback" in aviation) instructions and commands before fulfilling them. This readback step is vital in aviation communications as it supports verification. Although previous research analyzes readback related to memory (Schneider, Healy, and Barshi 2004), our project focuses on shadowing's effect on attention. In line with previous findings, we believe that perfectly continuous readback would cause deficits in command comprehension. This unwanted effect is due to shadowing taking up too much of attention's resources by itself. However, we expect overall attention to improve when implementing partial-shadowing for the required drilling tasks. Consequently, a verbal shadowing step is part of the proposal for the UDL. We believe that consistently incorporating a verbal shadow within training and development sessions will help tune the drilling personnel deeper into their tasks and create a better-integrated communication network.

3. EXPERIMENTS AND METHODS

Our experiments are designed to understand better and quantify the impact of communication and attention on drilling performance. Their ultimate goal is to prove that if communication-related human factors are consistently effective between participants, then drilling task performance improves. The "Driller's Roadmap" (DRM) is a "human-in-the-loop" experiment in which verbal requests vary across multiple testing phases and multiple levels of task complexity. The "Verbal Shadow Drilling Study" (VSDS) is a similar experiment in which a verbal shadowing intervention helps to mitigate varying levels of external distraction. Together, the uniqueness of these experiments is that final results are quantifiable: time to task completion, rate of task completion, and the total number of subjective errors. Another uniqueness of this experimental series is that it also serves as a communication training course for the research participants.

3.1 Experiment 1 – Driller's Roadmap

This section describes the DRM Experiment, including participants, equipment, phases, and procedures. The experimental setup includes a portable real-time drilling and well control simulator and two human participants. After simulator warmup exercises, each participant is randomly assigned a role and briefed on their responsibilities. The experimental procedures commence after the briefing.

3.1.1 Participants

The DRM requires two participants: Participant 1 is assigned the role of Driller. According to the Schlumberger Oilfield Glossary (2020), a driller is "the supervisor of the rig crew… and is responsible for the efficient operation of the rig site as well as the safety of the crew […]. Their role is to supervise the work and control the major rig systems. The driller operates the pumps, drawworks, and rotary table via the driller's console" This definition underscores the importance of precise language by highlighting the Driller's expectations of efficiency and safety. Thus, our experiment uses this same definition but applies it to our simulated drilling environment. Participant 2 is assigned the role of Assistant Driller (AD), and their responsibilities are unique for each of the experiment's three phases, the most important being communication, not actions. The AD is "hands-off," not allowed to touch any of the physical consoles during the experimental procedures. Instead, the AD communicates drilling parameter changes (according to each phase's rules and "roadmap") directly to the Driller, who must safely operate the simulator's control panels. The Driller is allowed to communicate at any time and in any manner. Their shared goal is to virtually drill the well according to a preconfigured "roadmap" of parameter changes. Participant pairs should represent combinations of undergraduate students, industry-experienced grad students, and professional drillers.

3.1.2 Setup

This experiment requires only two simulator consoles: a drilling console and a touchscreen panel. The experimental design is intentionally simple, so the simulator's other consoles (BOP panel, remote choke, and manifold) are used for warmup exercises only. The simulator is organized on a standard work table (Figure 2) with the drilling console and touchscreen panel in front of Participant 1's chair (right). Participant 2 sits to the left with a clear sight of both consoles. Because verbal communication is the variable of interest, wireless microphones are secured to each participant's shirt collar, and their communications are recorded for later analysis. Some participant groups attended this research-training during the middle stages of the COVID-19 epidemic. Masks are strictly worn, but this health and safety practice did not significantly affect the sound quality of voice recording.

Figure 2: DRM equipment setup (left); drilling console (right)

Because drilling actions are the dependent variable, the drilling console must display the corresponding parameters of pump stroke per minute (SPM), top drive revolutions per minute (RPM), and rate of penetration (ROP) in real-time. The Driller's console is home to all the necessary data displays (Figure 2, orange boxes), physical buttons, knobs, and drilling brake (Figure 2, blue boxes). The touchscreen student panel (Figure 2, left) is a graphical user interface that helps a simulator user visualize the drilling process more completely. Because many incoming participants have limited drilling or simulator experience, providing this secondary mode of data representation is very beneficial. While communication has some restrictions for the participants, they are both allowed (and encouraged) to observe all of the available data throughout the entirety of the experiment.

3.1.3 Phases and Procedures

The "Driller's Roadmap" experiment is a three-stage experiment (training, testing, learning), each with its own unique phases (Figure 5). Objective findings come from the testing stage, when each integrated phase uses a different set of communication rules. During the "Natural" phase, the Assistant Driller can use any words or phrases that he/she deems appropriate. During the "Imperfect" and "Perfect" phases, the researcher provides the AD with a script of words that must be read in a specific prescribed manner. The scripts vary the command phrases based on word usage, phrase length, volume, ambiguity, and more. Thus, the AD's verbal instructions are the experiment's independent variable, while the Driller's drilling performance is the dependent variable. The DRM's experimental design tests whether specific phrases will lead to improved or worsened performance.

The training stage consists of a warmup phase and a briefing. As in industry, each research participant comes to the training with various cultural backgrounds, primary languages, academic exposures, field experiences, and more. Because of this experiential diversity, the training stage establishes a baseline for drilling and simulator usage. Some participants have zero drilling experience, while others have zero simulator experience, so training on the simulator is a requisite phase. Furthermore, training familiarizes the participants with the dexterity necessary to operate this specific simulator and its consoles. The briefing phase provides a formal introduction to the DRM and conveys the roles and responsibilities to the participants. The briefing sets the rules before the testing stage and is especially important before the "Imperfect" and "Perfect" phases when communication commands are scripted.

The second distinct stage of the experiment is testing, in which the participant pairs attempt to complete the pre-determined drilling tasks with specific styles of communication. Each phase ("Natural," "Imperfect," "Perfect") has a unique objective, yet each phase uses an identical structure of time intervals and task complexity (Table 1).

Table 1: task structure of DRM

Tasks by complexity	*Beginner*	*Intermediate*	*Advanced*
Parameters requested	*RPM **or** SPM*	*RPM **and** SPM*	*ROP*
Time interval	*30 secs*	*60 secs*	*120 secs*
Tasks per phase	*10*	*4*	*1*

Task complexity for the DRM is defined as varying levels of difficulty based on the required/expected number of steps or length of time to completion. Beginner-level tasks are single parameter changes, intermediate-level tasks are double parameter changes, and advanced-level tasks require simultaneous parameter changes plus continuous monitoring. Beginner- and intermediate-level tasks are a combination of SPM and/or RPM settings, while advanced-level tasks are ROP settings. This range of task complexity simulates the wide range of tasks experienced daily at the rigsite. Ultimately, different task complexities help to test the efficiency of communication for simple situations versus complex (or more stressful) ones.

Time intervals for the DRM are important for data collection and the overall efficiency of the experiment. This interval method enables the experimenter to have a properly defined 'start' and 'stop' time for each task, knowing that some requested tasks might not be completed at all. Only a certain amount of time is allotted for each drilling task, and a preconfigured app facilitates this interval schedule. The participants understand to proceed to the next drilling task when the app makes an audible alert tone. A single phase of testing is 15 total drilling tasks and takes approximately 9 minutes to complete (according to the task structure defined in Table 1)

The "Natural" phase allows communication between participants without restriction. The phase's primary objective is to establish an objective performance baseline while simultaneously observing the participants' intuitive communication skills. The researcher's subjective observations are shared during the debrief phase and are very important for the long-term development of the UDL. Practically, the "Natural" phase helps to differentiate an "average" day of work from a "bad" or "perfect" one.

The "Imperfect" phase represents that "bad" day of work. The researcher provides the AD with a prescribed script of 15 drilling task commands that they must dictate to the Driller during each time interval. These 15 phrases are based on a review of effective (and ineffective) communication skills. Examples of these Phase B scripted commands are given in Table 2. "Imperfect" phrases highlight the importance of appropriate volume, timing, relevancy, specificity, logicality, and more. We expect drilling performance to suffer during this phase. However, we are also looking to observe any frustrations or antagonistic interactions between the AD and Drillers.

Table 2: "Imperfect" phrase examples for the DRM

Example #	Scripted "Imperfect" Phrase	How To Say It
1	"Drill no faster than 90 feet per hour"	Normal volume, normal pace
2	"Without changing weight on bit, without changing pump strokes, change the rotation to revolutions per minute of 110"	Normal volume, **slower** pace
3	"Pump at 140 strokes per minute"	**Wait 10 seconds**, then normal volume, normal pace
4	"Decrease pump strokes to 80 SPM"	**"Whisper"** volume, normal pace

The "Perfect" language phase also uses 15 scripted drilling commands. While the "Imperfect" phrases remain static, the "Perfect" phrases must evolve as we conduct more research, collect more results, and receive valuable feedback from participants. These early "Perfect" phrases must be fine-tuned to help create the foundations for the long-term goal: the Universal Drilling Language. Our future language studies will prove that some communication protocols are more effective than others, so the UDL and its "Perfect" phrases will need to iterate to match. Table 3 provides some examples of how the DRM uses "Perfect" phrases; the example numbers and task objectives are maintained from Table 2 for consistency.

Table 3: "Perfect" phrase examples for the DRM

Example #	Scripted "Perfect" Phrase	How To Say It
1	"Increase weight on bit to 35k and drill at 85 feet per hour"	Normal volume, normal pace
2	"Increase RPM to 110"	Normal volume, normal pace
3	"Decrease strokes to 140"	Normal volume, normal pace

The debrief is an essential phase for mutual learning to occur. First, the participants provide general and subjective feedback for their performance before being shown their measurable results. Next, the participants provide specifics about how the "Imperfect" and "Perfect" phrases uniquely affected their performance. This feedback is vital for understanding the psychological impacts of imposing a "Perfect" language, and the researcher also explains the how and why of the "Imperfect" communication principles. Lastly, the researcher uses this debrief phase to give actionable feedback to the participants based on subjective and measurable observations. Each participant exits the training feeling more capable of improving their speech in many other contexts (such as at the rig, in the classroom, in their marriage, etc.). Collectively, these debrief steps are educational and help connect the dots for the participants.

3.2 Experiment 2 – Verbal Shadow Drilling Study

Verbal shadowing is the primary intervention for the VSDS. If verbal shadows prove effective, then secondary mechanisms of cognitive improvements (such as verbal recalls) might be worth exploring. If shadowing is the immediate verification of a command, then a verbal recall would be the delayed verbal communication that confirms task completion. Our hypothesis-at-large is that updated communication procedures will help improve the cognition and focus of our drilling personnel. The proposed shadow-recall communication structure would provide a robust attention platform for a driller to maintain an improved balance between primary and distracter stimuli.

3.2.1 Participants

The VSDS requires only one participant. This participant must be fluent in English and self-report normal hearing and corrected-to-normal vision. Each participant simulates the role of Driller, which is defined the same as in the DRM. The Driller must operate the simulator's control panels (Figure 2), and their ultimate responsibility is to drill according to the researcher's drilling parameters requests. Participants should represent a balance of undergraduate students, industry-experienced grad students, and professional drillers.

3.2.2 Setup

The VSDS requires both a physical equipment setup and a set of experimental stimuli. The physical equipment needed is only two simulator consoles: the drilling console and a touchscreen panel. While the real-time drilling simulator is the same as the previous experiment, the VSDS adds two distinctive features to the setup: a speaker system and an external display. The speaker system is a 2-channel stereo, using the standard audio output from the lab's secondary laptop with internet access, and its function is to transmit audio stimuli. The output volume of the stereo system is adjusted to transmit at an approximate output of 80 decibels. This output level simulates indoor conversation (60 decibels) plus background noise (additional 20 decibels) from the drill floor to match industry estimates (WorkSafeBC 2018). The left speaker is positioned 5 feet (30 deg anterior) from the participant's left ear, while the right speaker mirrors the positioning to the right.

The external monitor is a 47-inch display, and its sole function is to transmit the audio-visual distractor stimuli mentioned in the following subsection section. The monitor's position is in the participant's background field of vision, approximately 3 feet behind the DS-50, at eye level, and almost entirely in unobstructed view. The monitor connects to the lab's secondary laptop using the extended display functionality. Not shown, but the researcher also uses a lap timer to record how long each drilling task takes to complete. The full equipment setup is shown in Figure 3.

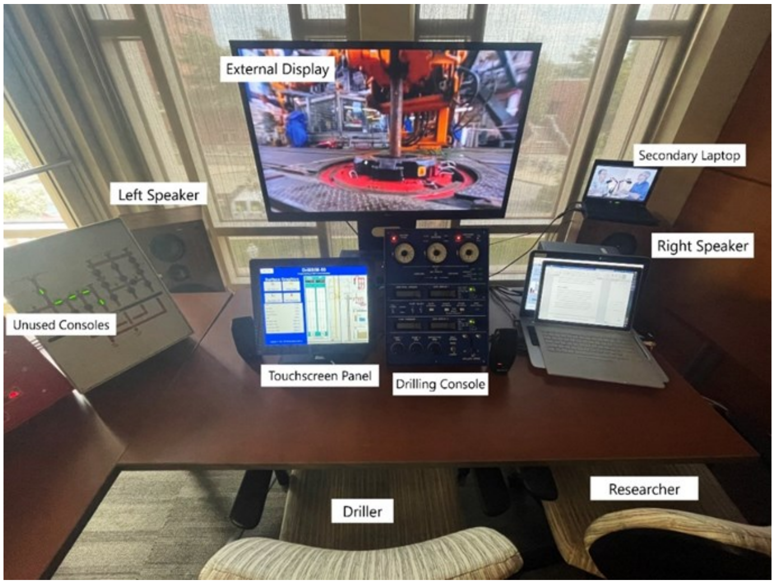

Figure 3: VSDS equipment setup

There are multiple sources of input stimulus required for this experiment, which includes verbal drilling commands and three sets of audio/video stimuli: 1) active-control "natural" soundscape, 2) general-purpose "rig white noise," and 3) a conversational distractor.

Like the DRM, this experiment also isolates parameters from the three fundamental systems (circulation, rotation, weight) by requesting changes to the rotary speed of the top-drive system (TDS) in revolutions per minute (RPM), pump speed in strokes per minute (SPM), weight on bit (WOB) in thousand-pounds (k-lb), and rate of penetration (ROP) in feet per hour (FPH). However, this experiment also adds bit depth in feet and slips status. The researcher verbally requests drilling parameters (input), and the participant Driller manipulates the drilling simulator (output) accordingly. Examples of these input task phrases, systems, and outputs are presented in Table 4.

Table 4: examples of VSDS drilling task requests

Example #	Verbal Command	Systems	Outcome
1	"Increase pump strokes to 100"	Circulation	Flow begins
2	"Increase RPM to 140"	Rotation	Drillstring movement initiates
3	"Drill ahead using 20k weight on bit"	Weight	Bit touches bottom, drilling begins
4	"Increase RPM to 160"	Rotation	Torque increases, ROP increases
5	"Increase pump strokes to 130"	Circulation	Pump pressure increases, return flow increases

This experiment keeps downhole drilling conditions constant. In reality, there are thousands of surface and downhole variables to consider within drilling. Fortunately, the simulator used herein comes equipped with advanced and accurate software enabling real-time calculations of complex downhole conditions like gas expansion and migration, pressure gradients, and rate of penetration changes (just to name a few). This deep customization enables simulator users to experience a wide range of drilling rig scenarios such as drilling ahead, tripping pipe, and well control events, all at the click of a button. However, our experimental design isolates a single drilling scenario to minimize the variability between participants. During experimental design, the researcher preconfigures a set of surface and downhole variables, then saves the scene as a snapshot to be run and rerun across different participants and drilling sessions. This snapshot allows for 23 feet of uninterrupted and homogenous drilling before any lithology changes. Based on the prescribed drilling tasks and the intended ROP, the 23 feet mentioned previously is more than what each participant will drill through. Most participants might only drill ahead by about 5 feet.

All experimental sessions use the same drilling snapshot for consistency because we want objective results derived from the driller's actions, inactions, and communications surrounding each simulated drilling task and not from the drilling environment.

The VSDS experiment also requires a panel of stimuli which includes verbal phrases, audio distractors, and video distractors. The verbal drilling requests (examples like Table 4) are "perfect" phrases developed from the DRM and UDL methodology. As it pertains to the audio and video distractors, the overarching goal is to test if effective communication techniques (like verbal shadowing) can aid a drilling team despite the distractors being present. These simulated distractors are sights and sounds that any drilling team can expect at the rig site, in the drillshack. Our experimental procedures require two unique sets of background stimuli: one for an active-control phase and another for the testing stages. Both stimuli sets are industry-relevant, but what differentiates them is the intended level of arousal (or distraction). We could exclude audio and video entirely from the control stages, but we create an active-control scenario instead by using decibel-matched audio and video. These distractions are replicated in the lab because all rigs, regardless of application or location, are noisy and ever-present with environmental interference.

The active-control stimuli need to be as non-distracting and focus-inducing as possible since low-arousal background noises have been shown to produce a less significant interference effect (Han et al. 2013). Our active-control stage uses a video of rainfall for the background audio and visual stimuli. Since background noise is inevitable at the rig site, this "natural" soundscape seems as low-arousal and focus-inducing as possible, as suggested by (DeLoach, Carter, and Braasch 2015).

The VSDS testing stages, in contrast, must include distractors that represent the average noises and distractions present at the rig. The stimulus chosen for our experiment includes moving machinery (e.g., drawworks, iron roughneck, elevators, automatic slips), humming motors, and the occasional beeping alarms. One can think of this distraction as general "rig white noise." You will find these noises at every rig in the world, and so for this reason, we include them in our study of a driller's attention. This general-purpose audio/video distractor comes from a drillship building a stand of drillpipe on the auxiliary side of the rig floor. Building up extra/future drilling strings using auxiliary rig equipment is an everyday operation available to most modern simultaneous operating (SIMOPs) rigs. Plus, as a reminder, any SIMOPs working environment is generally high-risk and a prime candidate for implementation of our UDL. This video stimulus is also helpful because it provides a realistic view out of the driller's cabin while synchronously matching the "rig white noise" audio. Altogether, this distractor helps increase the level of realism in this simulated drilling scenario.

A secondary audio stimulus is a conversational distractor. In a practical sense, this might be an ongoing conversation inside the drillshack (behind or around the active drilling personnel) that is not immediately relevant to the task at hand. A distracting conversation (like the cocktail party effect) is often as irrelevant as friendly banter about sports, politics, weather, or future/past days off. Other times, these conversations might be more rig-relevant such as about future or ongoing operations elsewhere on the rig. From years of field experience, our research team understands that the active drilling personnel is often listening to (if not actively taking part in) these distracting conversations. For these reasons, the VSDS experiment uses a drilling podcast for the conversational distractor, which seems suitable for diverting a driller's attention. This drilling podcast episode offers many opportunities for a driller to be distracted by industry-specific and salient details. Discussion includes many references to numbers (pricing, rig counts, money), oilfield locations (Houston, TX), standard oilfield equipment and activities, among other drilling-related topics. The vision of the VSDS is for verbal shadowing to act as a "barrier" to these distractors by helping a driller focus their attention on the drilling tasks at hand.

3.2.3 Phases and Procedures

All sessions of this attention study include customizable phases followed by standardized experimental phases. The customizable phases include a general tour of the drilling simulator center, a general lecture on fundamentals to drilling, and simulator training exercises. These phases are customizable in length and intensity due to each participant's unique starting point in terms of experience and knowledge. The objective of these learning stages is to teach participants the basics of drilling (if expertise is limited) and consequently bring all participants to the same baseline level of performance.

The experimental stage of the VSDS includes three different phases: Active-Control, No-Shadow, and With-Shadow. The Active-Control phase represents the optimal drilling scenario, where there would be zero distractions. This phase sets a performance baseline before later phases introduce elements of distraction and attention. This first phase is considered an active control because the non-distracted drilling includes a neutral and non-distracting audio-video stimulus (the natural rainfall audio/video, Figure 4).

The simulator's drilling scenario is reset before proceeding to either the No-Shadow or With-Shadow phase. The No-Shadow now introduces some of the realistic distractions to the Driller. Two audio distractors (general-purpose rig white noise and drilling podcast conversation) replace the neutral rainfall stimulus, while the video distractor of rig equipment moving replaces the neutral rainfall stimulus. This phase is considered distracted drilling *without* any required verbal shadowing. The With-Shadow phase uses the same audio and video distractors, but with one major exception: the Driller must now provide a verbal shadow to each of the researcher's drilling command requests. This phase also requires an additional practice exercise so the participant can learn what the verbal shadowing technique is and how to use it. The With-Shadow phase cannot begin until the participant is comfortable and confident with the prescribed technique. Now, the phase is considered distracted drilling *with* verbal shadowing. We posit that this communication intervention will have an attention-focusing effect, as well as performance gains.

Across all three experimental phases, the researcher verbalizes the drilling commands while the participant Driller attempts to complete each using the drilling simulator. The researcher uses a lap timer to see how long each task takes to reach completion. Each phase is complete after the Driller completes all 25 available drilling tasks, or 5 total minutes have passed, whichever comes first.

4. DISCUSSIONS

Our experiments are taking human factors research and simulator training to the next level. This research series is far more practical than the previous. Instead of merely summarizing and repeating the industry's previous lessons learned, we are now learning more by putting our drilling humans "in-the-loop" of the research.

More specifically, the experiments described herein provide insights into the human factors topics of communication and attention. The difference between our two experiments relates to their primary objectives. The first tests whether the content of our communication can produce an objective difference in drilling performance. By using two research participants, we can observe how drillers naturally speak and then prompt them to communicate in ineffective and newer effective manners. We expect a number of findings, both objective and subjective. We expect the time to completion for drilling tasks to increase for "Imperfect" phrases and for the participants to express feelings of frustration with their partner. Furthermore, the tasks with higher levels of complexity will likely suffer worse. We believe that time to task completion will decrease during "Perfect" communications, and the rate of completion will increase. With successful trials, this experiment leads to a fundamental framework of better commands and phrases to be used in drilling, ultimately leading to a more comprehensive Universal Drilling Language. This experiment will improve drilling outcomes while also increasing the confidence of our humans.

The second experiment in this series builds on the communication findings but adds variables of distraction. This extra layer of distraction, along with the verbal shadowing intervention, will lead us to understand how our drillers' attention might be better managed. By using the "Perfect" phrases developed from the previous experiment, we can also continue to refine and test the effectiveness of specific phrases. The verbal shadowing intervention is expected to help most of the participants while potentially hurting the performance of others. We expect similar objectives as in the previous experiment – consistent use of the intervention will lead to better drilling performance and safety. From a subjective standpoint, we expect some participants to experience the cocktail party effect due to the conversational distractors. We also believe there will be some mixed performances due to the boundaries of multi-lingual participants and the variability of shadowing skills. Overall, this approach will likely be a net-positive outcome, but collecting critical feedback on these ideas is essential.

By making the human our variable of interest, we can begin to optimize human performance within a defined drilling system (or application like geothermal). This broader shift of mindset and research methodology will enable us to fine-tune and change our people's behaviors leading to greater efficiency and safety. The long-term goal is to optimize the human sides of the equation, just as much as we are optimizing the technology, algorithms, etc.

5. CONCLUSIONS

The drilling industry is always looking for improvements which is even more important for the up-and-coming geothermal sector. From our humans to emerging technologies and innovative ideas, the room for improvement is vast. The potential for reducing non-productive time, reducing risk, drilling faster, improving safety, improving environmental impacts, and more will depend on a balance of technical and human improvements.

Our proposed training series suggests that our student and professional populations might see significant improvements in their behaviors and communication skills thourh "human in the loop" dedicated training packages.

If the geothermal drilling sector adopts a dedicated drilling language, its companies will benefit significantly of dedicated universal drillin language. Consistency across all types of tasks with varying levels of risk and complexity will happen, processes will become safer and more repeatable, and the other drilling sectors will eventually benefit.

There is a great depth of potential for future directions and research applications shared in this paper. This research project aims to bridge the gap between the industry's humans, machines, and algorithms. And due to the high cognitive demands of the sector's jobs, it remains of the utmost importance to keep progressing our knowledge about human factors.

The next generation of drilling systems needs to be flexible enough to adjust their operation based on the human factors also at play – attention, and communication from our examples. Future drilling systems that can efficiently assign resources to automated or human processes will become the safest, fastest, and most sustainable options. A human-in-the-loop drilling system should continuously monitor the cognitive workload and attention of its human driller operator.

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