Decision-Making Biases in Cybersecurity

Measuring the Impact of the Sunk Cost Fallacy to Delay Attacker Behavior

by

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ABSTRACT

Cyber operations are a complex sociotechnical system where humans and computers are operating in environments in constant flux, as new technology and procedures are applied. Once inside the network, establishing a foothold, or beachhead, malicious actors can collect sensitive information, scan targets, and execute an attack. Increasing defensive capabilities through cyber deception shows great promise by providing an opportunity to delay and disrupt an attacker once network perimeter security has already been breached. Traditional Human Factors research and methods are designed to mitigate human limitations (e.g., mental, physical) to improve performance. These methods can also be used combatively to upend performance. Oppositional Human Factors (OHF), seek to strategically capitalize on cognitive limitations by eliciting decision-making errors and poor usability. Deceptive tactics to elicit decision-making biases might infiltrate attacker processes with uncertainty and make the overall attack economics unfavorable and cause an adversary to make mistakes and waste resources. Two online experimental platforms were developed to test the Sunk Cost Fallacy in an interactive, gamified, and abstracted version of cyber attacker activities. This work presents the results of the Cypher platform. Offering a novel approach to understand decision-making and the Sunk Cost Fallacy influenced by factors of uncertainty, project completion and difficulty on progress decisions; results demonstrate these methods are effective in delaying attacker forward progress, while further research is needed to fully understand the context in which decision-making limitations do and do not occur. The second platform, Attack Surface, is described. Limitations and lessons learned are presented for future work.

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CHAPTER 1

INTRODUCTION

Cybersecurity is an arms race (Limnéll, 2016) and the fight against cybercrime has moved inside the network. Data can be stolen, services interrupted, and systems destroyed once a network perimeter security is breached. Technological solutions to cyber threats dominate the landscape (e.g. security architecture, artificial intelligence, machine learning) (Hodo et al., 2017; Raponi et al., 2019). Defensive strategies need to move from a reactive or passive defense to a proactive strategy that focuses as much on human actors as it does the technological solutions.

In most cases, cyber attackers have a disproportionate advantage over defensive teams (Fugate & Ferguson-Walter, 2019). For example, a single threat actor can obfuscate malware to avoid detection methods using sparse infector viruses, encrypted viruses, and polymorphic code (Easttom, 2018). Masked as normal user traffic and self-deleting, attackers can hide and infiltrate, achieving their goals before defenders are aware (Canham et al., 2018).

Cyber ops are a complex – sociotechnical system

Cyber operations are a complex *sociotechnical* system (Knott et al., 2013) where humans and computers are operating in environments in constant flux, as new technology and procedures are applied. Attackers and defenders play a dynamic game of cat and mouse. Novel defense strategies trigger new attacks, to which new defenses respond, and so on. Once inside the network, establishing a foothold, or *beachhead*, malicious actors can collect sensitive information, scan targets, and execute an attack. In military terms, a "beachhead is a designated area on a hostile or potentially hostile shore that, when seized and held, ensures the continuous landing of troops and material, and provides maneuver space requisite for subsequent projected operations ashore"(*Joint Publication 1-02: Department of Defense Dictionary of Military and Associated Terms*, 2011). Unbeknownst to defenders, the foothold allows attackers to persist in a network for months or even years as they plan and prepare.

Cyber deception to delay malicious actors

Increasing defensive capabilities through cyber deception shows great promise by providing an opportunity to delay and disrupt an attacker, once network perimeter security has already been breached (De Faveri et al., 2017; K. Ferguson-Walter et al., 2017; Shade et al., 2020). Deception can be defined as the provision of misinformation that is realistic enough to confuse situational awareness and to influence and misdirect perceptions and decision processes (K. Ferguson-Walter et al., 2019). "Deception provides visibility into exposed attack paths, attacker activity, and captured threat intelligence" (Steingartner et al., 2021, p. 2). In this way, deception, focused on the human actors, can camouflage and move the attacker's beachhead to a strategic location of the defender's choosing (Harknett, 2021).

In the first generation of cyber deception*,* technological advancements involved decoys or honeypots and Intrusion Detection Systems (IDS). The next generation of deception includes the psychological deception of human actors. The mind of the adversary is the ultimate target of deception (Ormrod, 2014). Thus, an understanding of how people interact with technology, or the human factors, within cyber environments is essential for securing critical assets (K. Ferguson-Walter et al., 2017). For example, the Stuxnet worm, a cyber-attack on Iranian uranium centrifuges, caused a disruption by providing false information readings to operators which left them blind to the attack and resulting mechanical failures (Chen & Abu-Nimeh, 2011; Farwell & Rohozinski, 2011; Langner, 2011). This attack achieved success in part because of delivery method (compromised USB drives that crossed the air gap onto isolated machines not connected to the internet) and because of the presentation of false information to human controllers. In other words, it is not just the cyber vulnerabilities (the actions of the malware itself) that are exploited, but also the human factors (willingness to use those USBs, and difficulty interpreting data from the centrifuges when it was falsely representing the state of the world).

Human Factors – Oppositional Human Factors

Traditional Human Factors research and methods are designed to mitigate human limitations (e.g., mental, physical) to improve performance. These methods can also be used combatively to upend performance. That is, Oppositional Human Factors (OHF), seek to strategically capitalize on cognitive limitations by eliciting decision-making errors and poor usability. Applied as a cyber defense, the goal of OHF is to expose, magnify, and explicitly induce known limitations and deficiencies in the performance of cyber attackers (Gutzwiller et al., 2018).

Cognitive limitations that lead to Biased Decision-Making

Human cognition is sophisticated and complex. Nevertheless, humans do not model the world with complete accuracy. Humans use satisficing strategies, in which the world is modeled *close enough* to reality. Simon (1955) defined this type of reasoning as bounded rationality in which human computational and deliberation capacity is limited. Bounded rationality is “approximate rationality” (Simon, 1955, p. 114). When making choices, instead of spending hours thinking about every option, people use mental shortcuts, or heuristics. Discovering all possibilities from which to carefully consider the best option would consume too many resources (tangible, mental, and physical) (Fiske & Taylor, 1991). For the most part, this type of quick decision-making works very well. Humans do not necessarily seek the best answer, but often one that is good enough. Dual process theory provides an explanation for this phenomena by differentiating between deliberate energy consumptive thinking, and intuitive, automatic and less effortful thinking (Evans, 2011). Kahneman (2011) proposed the intuitive and automatic thinking type as System 1, and deliberate thinking as System 2. Because real-life decisions involve uncertainty (probabilities and consequences) and are normally time-bound, people often default to using System 1 thinking. Occasionally in these situations, heuristics - or decision-making biases - result in less optimal outcomes. Decision-makers must be careful of following intuitions, especially when the facts show an alternative is better. Spottswood (2013) describes System 1 as “implicit rather than explicit” which means, “we are aware of our conclusions but not the process that produced them” (p. 156), whereas System 2 is explicit, so is “available to introspective awareness” (p. 166).

System 1 allows us to make quick choices and perform automatic activities, System 2 allows us to think things through, while considering facts and previous knowledge.

Applying Biases to Cyber Situations

Cyber consists of complex and dynamic situations in which decisions are of high consequence. Information in cyber environments is also, very often, incomplete, and uncertain. As a result, cyber operators must at times employ intuitive decision strategies (e.g., Kahneman & Tversky, 1984; Tversky & Kahneman, 1981a; Tversky et al., 1988). These decision strategies are formed from a simplified model of the world and are often efficient and effective, (Gigerenzer & Goldstein, 1999; Goldstein & Gigerenzer, 2002; Hogarth & Karelaia, 2006) yet may still result in judgement, or *decision-making bias*. These heuristics often allow rapid, highly accurate decisions to be made on the basis of pattern recognition and experience (Ericsson & Charness, 1994; Gigerenzer, 2008; Kahneman & Klein, 2009; Klein et al., 1988). For example, Kelley and Jacoby (1996) found that when making comparisons about the difficulty of anagram solutions, judgments based on subjective experience was a highly valued heuristic, if not entirely accurate (for more recent research, see Frank and Kuhlmann, 2017). In certain circumstances, decision-makers may make mistakes that are systematic and predictable (Gilovich & Griffin, 2002). For example, Kumbasar et al., (1994) reported a consistent egocentric view of unrealistic individual importance and connectivity within social structures which led to an over-valuation of self-importance in peer groups. Gneezy (1996) found in an experimental lottery game, subjective probabilities of winning a single game had a greater influence on participants' estimated probabilities of winning multiple rolls in a row than the cumulative judgement of success. Zhou et al., (2014) studied drivers' risk attitudes in route choice behavior under real-time road conditions and reported that the sensitivity to lost travel time was predictably related to risk tolerance.

Moving the research forward – experimental elicitation of biases

Within the last few years, researchers have begun to research the occurrence of human decision-making bias within the cyber operational domain (J.A.O.G. de Cunha & de Moura, 2015), and with a specific focus on the effects of decision-making biases as a defensive strategy against attackers (K. Ferguson-Walter et al., 2019; R. Gutzwiller et al., 2018; R. S. Gutzwiller et al., 2019; C. K. Johnson et al., 2020, 2021). However, research to experimentally elicit decision-making bias in multi-step, adversarial cyber operations (e.g., proceeding through the stages in an attack such as performing network reconnaissance and escalating privileges) has not been completed.

Deceptive tactics to elicit decision-making biases might infiltrate attacker processes with uncertainty, and "make the overall attack economics unfavorable" (Steingartner et al., 2021, p. 4). Deceptive strategies could cause an adversary to make mistakes and waste resources; for example, spending too much time on one element of key terrain, such as the domain controller, rather than going through another more efficient route to reach a designated target. This might be particularly disruptive when multiple high value targets have already been identified, and an attacker would clearly benefit in moving to one of the new targets. In this case, an attacker may be spending all their time on local optimization, rather than analyzing global opportunities to achieve a goal. Inducing decision-making bias in an attacker is a novel, deceptive approach to misinform, confuse, and misdirect decision processes providing an opportunity to tip the scales in favor of defensive, strategic capabilities.

Does the previous bias theory fit in a complex, cyber arena?

From the domain spanning range and decades of research on decision-making biases, we understand these can be elicited in single-decision making scenarios. But how does the research apply to ongoing, time-constrained, and multi-step decisions in a diverse and complicated situation like cyber defense? That is, how can research provide answers to more realistic, time-dependent decision-making? Simply stated, the previous research on cyber defense with humans and decision-making biases stops short at notional or very simple, construed, single decision situations.

The Sunk Cost Fallacy

There are hundreds of decision-making biases that have been under scrutiny over the past few decades (C. K. Johnson et al., 2020). As such, we focused on a specific bias that appears to be especially beneficially to cyber defense: the Sunk Cost Fallacy (SCF). With a better understanding of attackers' decision-making limitations, we can delay and disrupt their ability to cause severe damage inside the network.

Arkes and Blumer (1985) defined the Sunk Cost Fallacy as the tendency to continue with a specific strategy because of prior investments which take the form of money, effort or time. Cyber defense strategies might make use of the Sunk Cost Fallacy to elicit problematic thinking in attackers because the bias operates at a subconscious level. That is, even in the face of some evidence that the current activities or projects are more costly than an alternative, people value their historical expenses more than it is worth.

Two Decision Types – Utilization and Progress

Two main decision types have been used in studies to evaluate sunk costs based on either (1) utilization decisions made within a static scenario, or (2) based on progressive decisions made over time. In Utilization research, stimuli are single decisions problems presented as a fictitious situation with imaginary role playing where the choice is made between two equally attractive options. The effects of the Sunk Cost Fallacy are demonstrated as the preference for the option with costs already spent (i.e., sunk). In Progress research, data is collected from real-world, historical accounts and contain decisions made over an entire series as part of a broader course of action. The event data have (1) a specific start and end date, (2) an initial investment, and (3) additional investment over time. The effects of the Sunk Cost fallacy are demonstrated in failing projects when decision-makers persist cutting losses and going with another course of action.

Problems with previous research

Foundational research on the Sunk Cost Fallacy has primarily focused on utilization decisions investigated with single-decision scenarios that are not useful to understand decision-making in applied, dynamic cyber operations. The evidence for uncertainty as a factor in considering alternate options is contradictory with some authors contesting that uncertainty heightens the effects of the Sunk Cost Fallacy, while others purport that uncertainty plays no role. The few studies that focus on progress decisions include project completion impacts decisions to persist in a current project or not. Finally, of the three resource types, evidence for mental effort, a critical factor in cyber security activities, is sparse and inconsistent.

Project Goals

We know, in the real world, or at least in more complex and dynamic situations, no previous research addresses the core of everyday, operational, multi-step malicious cyber actors and campaigns. This project proposed to validate the existing literature, test our hypotheses in human subject experiments, examine the context and surrounding factors in which the Sunk Cost Fallacy occurs by designing a novel research approach.

Novel Experimental Platforms

By developing an innovative, gamified platform, we sought to create an environment that could elicit and measure the Sunk Cost Fallacy over the course of an interactive gamified version, balancing laboratory control with ecological validity, in an abstracted hacking task. Deterding, et al., (2011) presented gamification as "using game design elements in non-gaming contexts" (p. 2425). In the realm of human-computer interaction, a game "characterizes rule-based playing with determined goals" (Groh, 2012, p. 39). In addition, gamified cyber environments were reasonable for novice participants and represented more realistic conditions, missions, and tasks than static, historically popular surveys. Only one other study by Jiang, et al., (2020) tested the effects of the Sunk Cost Fallacy in an interactive, gamified platform. With the goal of collecting as many coins as possible in a window of time, participants collected coins from one of two locations with different rates of return. After collecting for a period, participants were offered a choice to stay, keeping all collected coins, or switch to a new location and start coin collection over. Even though participants detected a difference between each location, they overestimated the benefits of staying which signaled the effects of the Sunk Cost Fallacy.

In pursuit of the project goals, an experimental platform (Cypher) was developed to test decision-making biases in two experiments. The results then informed best practices to develop a second platform (Attack Surface) that increased the fidelity of adversarial cyber activities.

Cypher

In a simulated cyber environment, participants assumed the role of a cyber defender and solve encrypted passphrases to catch a cyber attacker. Participants had a limited number of resources (time, in-game currency) to help solve encrypted passphrases (e.g., cyphers). Using a provided alphanumeric table and key, participants solved *seven p*assphrases on one of two available portals (e.g., data server). A single decision point measured the effects of the sunk cost fallacy.

Attack Surface

Attack Surface (AS) paradigm represents a more cyber realistic environment in which participants will assume the role of a cyber attacker with a mission to infiltrate a large, corporate network to steal valuable information from the organization's data server. With a limited number of resources, participants will perform tasks to navigate through the secure subnets in the network. Subnets contain three types of hosts: personal computers, servers, and decoys. Tasks will simulate network reconnaissance to discover important details about each node, attack nodes to gain points and to advance deeper into the network. Multiple decision points throughout the network path measured the effects of the sunk cost fallacy.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Decision-Making Biases

Decision-making biases are consistent, pervasive, and operate in multiple domains of human performance (Murata et al., 2015). Decision-making bias in this context refers specifically to information judgement and processing and refers to both positive and negative influences. Decision-making biases are commonly referred to as heuristics; mental shortcuts that humans use to simplify decisions (Kahneman, 2003). Heuristics are successful cognitive adaptations to lessen the mental energy required in everyday decision-making by allowing highly accurate decisions to be made on the basis of pattern recognition and experience (Arkes, 1991; Ericsson & Charness, 1994; Gigerenzer, 2008; Kahneman & Klein, 2009; Klein et al., 1988). However, these mental shortcuts have costs as well as benefits (Archer, 1988). For example, engaging in a hobby you no longer enjoy, finishing an expensive meal after you are no longer hungry, or feeling anxious about violent crime after reading a news report about a metropolitan robbery even though you live in a city with a very low crime rate. Moreover, expertise does not exclude a person from biased decision-making. When decisions are made from incomplete information, experts do have an extensive knowledge base to pull from. However, research has shown that when using this knowledge to fill in the gaps, experts can make faulty assumptions that lead to inaccurate conclusions.

Hinds (1999) reported that experts were resistant to debiasing methods and underestimated novice performance on a novel task. That is, even with additional knowledge that novices performed well on a task, the experts continued to underestimate the novices' ability. Oskamp (1965) and Soll and Klayman (2004) found that in their related field of expertise, when given additional information, experts became increasingly overconfident in their abilities to make an accurate prediction. Overconfidence can lead to hasty decisions and little consideration for alternative options(Arkes et al., 1988)Thus, even experts fall victim to decision-making biases because aspects of their performance are beyond conscious awareness (Arkes, 1991; Fischoff, 1981; Wilson et al., 2013).

The complexity of human cognition: decision chains and intertwined biases

Decision-making biases are seldomly mutually exclusive (See Fig. 1). That is, multiple biases can interact and build upon one another, knitting together a foundation upon which a person's world entire view is based. For example, biases such as framing effects, aversion to ambiguity, and loss aversion, can each influence a person to succumb to the sunk cost fallacy, resulting in an escalation of commitment to a failing course of action (Staw, 1976; Staw et al., 1997; Staw & Ross, 1987; Staw, 1997).

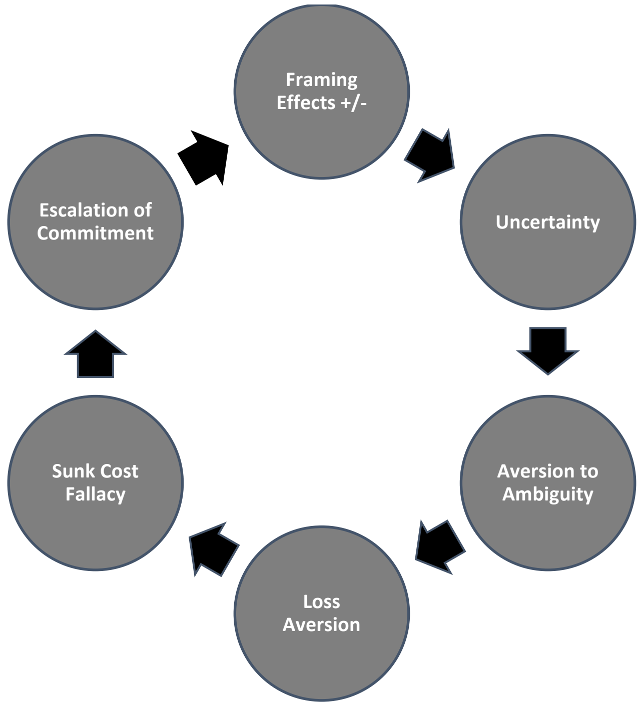

Figure 1. Decision Chains and Intertwined Biases. Under Framing effects, a project is presented from a point of loss or gain. Uncertainty can leave decision-makers vulnerable to ineffective choices. People tend to be averse to ambiguous or uncertain outcomes. Compounded with an aversion to loss in previous investment of resources, the sunk cost fallacy is made. In progress decisions - decisions made over the course of time - more resources are sunk into a project as an escalation of commitment takes hold.

In a chain of decisions that occur over time, biases can significantly impact even the most carefully planned project. For example, framing effects can positively or negatively influence a decision-maker by manipulating the perception of approaching a decision from either a point of loss, or a point of gain. In addition, an aversion to ambiguity takes the form of a decision-making bias when one chooses the 'sure thing', while avoiding the option with an unknown probability (L'Haridon & Placido, 2010). In other words, the uncertainty in whether a decision will result in a positive or favorable outcome leads a decision maker to avoid the ambiguous option (Bossaerts et al., 2010; Ellsberg, 1961; Frisch & Baron, 1988). This means that a better, but less certain option may not be chosen. People are generally loss averse meaning that when confronted with a decision, they generally choose avoiding losses over acquiring gains(Hastie & Dawes, 2001; Kahneman & Tversky, 1984; Kahneman & Tversky, 1979a; Shafir, 1993; Thaler, 1980; Thaler, 1993, 2000; Wicker & Hamman, 1995). Kahneman and Tversky (1979b) explain that loss aversion occurs because the potential pain of losing a resource exceeds the potential pleasure of gaining a resource. The pain of losing a resource (the sunk cost itself) when confronted with the choice of an alternative course of action, appears to be the driving force in the sunk cost fallacy. Uncertainty also plays a foundational aspect in decision-making biases; when they are uncertain about future outcomes, people become more averse to the potential risk of losing a resource and less willing to choose an alternative course of action.

In the cyber realm, decision-makers who invest a lot of resources in the attack process may tend to consider historical costs in assessing the value of a future outcome. This is poor decision-making because costs already spent should be evaluated as “sunk” and carry less weight in decision-making than current or incremental investments (Thaler, 1980). However, when coping with uncertainty in decision-making, humans are vulnerable to ineffective choices that lead to biased thinking (Carter, Kaufman, & Michel, 2007). Such vulnerabilities may lead to the decision to continue to work and escalate commitment to the failing course of action by allocating even more resources to the project, even though this decision is ultimately more costly and risky than abandoning the effort for an alternative, better choice (Ross & Staw, 1993; Staw, 1976; Staw et al., 1997; Staw & Ross, 1987; Staw, 1997).

Expected Utility Theory versus Prospect Theory: Predicates for the Sunk Cost Fallacy

Expected Utility theory predicts that in situations of uncertainty, all people are perfectly rational in the sense that past experience and emotion does not affect decision-making (Von Neumann & Morgenstern, 1953). Specifically, when making a choice, the expected utility of each option is calculated as the weighted average of the utilities of the outcomes, given the probabilities and utility of all outcomes of each option. Expected utility is the anticipated desirability or value. In other words, a rational decision maker will perfectly choose the option that maximizes the expected utility, in all situations. However, in real life, it is not possible to know the risk, probabilities, and outcomes of all available choices. Most decisions contain an uncertain amount of risk. Therefore, humans more often make estimations based on a small subset of incomplete information. These estimations or mental shortcuts lead to decision-making biases. Biases are the result of automatic processing that operates at a subconscious level, and serve to reduce decision-making complexity (Kahneman, 2011).

To address the limitations of Expected Utility theory, Prospect theory (Kahneman et al., 1991; Kahneman & Tversky, 1979) proposed that when dealing with risk, human limitations in cognitive capacity as well as uncertainty plays a large role in decision-making. Prospect theory essentially predicts that humans evaluate gains and losses differently, because outcomes based on probability are underweighted when compared to those that are more certain. People don't always engage in calculating the utility of something to make a decision; this underweighting of probabilities then contributes to risk aversion which occurs when an anticipated loss is psychologically more painful than the equally anticipated gains and therefore is chosen less often. When decision-making behavior is not consistent in the rational sense, it violates Expected Utility theory - decisions can seemingly contradict one's preferences, depending on the situation. Lichtenstein and Slovic (1971) called this a preference reversal, a "systematic change in preference" between two options that are normatively equivalent. They found that when placing gambling bids, decision-makers favored the amount to win over the probability of winning which led to inconsistent choices. Kahneman and Tversky (1979) further argued that preference reversals are encapsulated in the overall complex behavior of loss aversion. For example, when a choice is presented in a different frame (e.g., positive/gain, versus negative/loss), people make different decisions, tending to be risk averse when they are more certain the anticipated outcome will be a loss, but risk seeking if they anticipate a more certain gain (See Figure 2).

In addition, and relevant to sunk cost in particular, Kahneman and Tversky (1979) proposed that people assign different weights to incremental gains and losses, rather than to the final outcome. Thaler (1980) theorized that this is due to a process called mental accounting, in which resources are accounted for implicitly (e.g., in memory). The author provided this example of mental accounting in decision-making:

Mr. and Mrs. J have saved $15,000 toward their dream vacation home. They hope to buy the home in five years. The money earns 10% in a money market account. They just bought a new car for $11,000 which they financed with a three-year car loan at 15%.

Figure 2. Mental accounting in decision-making (Thaler, 1980).

In this example, the total cost to finance a new car over three years at 15% totals $15, 950, which is $950 more than Mr. and Mrs. J saved toward their dream home. A better financial decision would have been to pay cash for the new car.

Related to the sunk cost fallacy, Garland and Newport (1991) state that, "the way individuals organize and process information in their decision-making behavior" influences "the perceived utilities of persistence and withdrawal" (p. 57). In summary, people appear to pay more attention to short-term gains and losses, rather than the overall future outcome because that future is more uncertain.

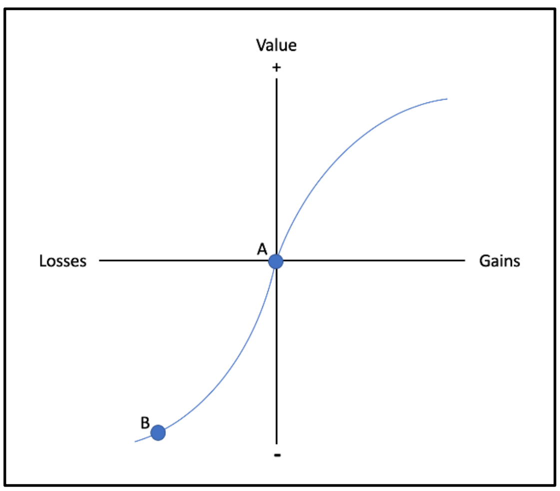

Figure 3. The value function of prospect theory (Kahneman & Tversky, 1979). Point A represents the initial investment. Point B represents a substantial, yet unsuccessful investment. At this point, "further losses do not result in large decreases in value:

however, comparable gains do result in large increases in value. Therefore, an investor at point B will risk small losses to obtain possibly large gains. Point B is the location of a person who has paid a sunk cost. Compared to a person at point A, a person at point B is more likely to make a risky investment." (Arkes & Blumer, 1985, p. 131)

Decision-Making and Framing. The perspective from which a situation is presented influences decision-making (Tversky & Kahneman, 1981b). The initial frame from which choices are made directly relates to risk aversion or risk seeking (Kahneman & Tversky, 1984). In addition, the "relative weight given to positive and negative features [of a choice] depends on whether subjects are faced with a task of choosing or rejecting entities." (Park et al., 2000; Shafir, 1993). In sunk cost fallacy, the decision-maker has invested resources into an endeavor to meet a pre-determined goal. The sunk costs are unrecoverable, and hence considered to be a loss. Again related to loss aversion, losses from the reference state (i.e. frame) carry more impact than gains (Park et al., 2000; Thaler, 1985). Conversely, in a situation framed with the potential for a reward, or gain, a decision-maker may become risk-seeking. In this sense, a person has nothing to lose and everything to gain. For example, whether a person must give up something already owned, versus giving up something they do not yet own, influences one to take more or less risks, respectively (see Figure 3). Interestingly, however, is the case when such great losses have occurred that the decision-maker escalates their commitment to the losing endeavor and invests even more resources, possibly in the attempt to recoup some of the previous losses. This is exemplified in horse race gamblers increasing risky bets on the final day of the race (Mcglothlin, 1956).

Providing examples of loss aversion and framing helps to untangle the complex and yet, interdependent nature of decision-making biases. Examples of loss aversion are the endowment effect (Thaler, 1980), the status quo bias (Samuelson & Zeckhauser, 1988), and the sunk cost fallacy (Arkes & Ayton, 1999; Arkes & Blumer, 1985; Staw, 1976). It is beneficial to briefly discuss the first two examples of loss aversion because they provide an expanded view of the impact on decision-making, before delving deeper into the phenomena of the sunk cost fallacy.

Endowment Effect. The endowment effect occurs once an item is owned, resulting in it having a perceived value greater than the market price. In other words, an owner of a good will demand more to give up an object, than they are willing to pay to acquire it (Kahneman et al., 1991). For example, Thaler (1990) conducted an experiment to demonstrate the endowment effect in which students were less willing to sell a ball point pen or mug at market price *after* each item was acquired. Once owned, the items became more valuable than the initial purchase price paid. Loewenstein and Kahneman (1991) demonstrated that an item's attractiveness or desirability is not a result of the reluctance to sell, but the pain of letting it go.

Status Quo Bias. The status quo bias is the tendency to stick with the current status of something, essentially "doing nothing or maintaining one's current or previous decision" (Hartman et al., 1991; Samuelson & Zeckhauser, 1988, p. 7) because the "disadvantages of leaving [the initial decision] loom larger than the advantages" (Kahneman et al., 1991, pp. 197–198). Samuelson and Zeckhauser (1988) reported factors influencing the status quo bias: (1) rational decision making in which uncertainty, costs and benefits are assessed; (2) cognitive misperceptions related to loss aversion; and (3) psychological commitment that involves sunk costs, social norms and the need to feel in control (Samuelson & Zeckhauser, 1988). For example, Kim and Kankanhalli (2009) conducted research on the status quo bias in user resistance to new information systems implementation within an organization. The authors reported that switching costs (i.e., transition costs, uncertainty costs, and sunk costs) are key constructs in the status quo bias that contribute to increased user resistance to the implementation of new technology.

Sunk Cost Fallacy

Humans tend to continue with a specific strategy because of their prior investments, which take the form of money, effort, or time. (Arkes & Blumer, 1985). Costs already spent should, rationally speaking, be evaluated as 'sunk' and carry less weight than current or incremental investments (Thaler, 1980). Manifested as the sunk cost fallacy, for example, these prior investments lead to the decision to continue to work (e.g., ongoing commitment) on a task *even though this decision is more costly*. Decision-makers stay with an initial course of action even in the face of objective failures, and when a less costly alternative option is available. According to Prospect Theory (as previously discussed), the Sunk Cost Fallacy relates to loss aversion in which the potential pain of losing a resource is greater than the potential pleasure of gaining a resource (Kahneman & Tversky, 1979). In Prospect Theory the value function for a loss is steeper than that for a gain (for a complete discussion about resource gains, see Tversky & Kahneman, 1992)

There is a large scope of research on sunk cost fallacy which exists. The topics and fields of application are broad; ranging from economics (Akerlof, 1991; Kahneman & Tversky, 1979a; Prelec & Herrnstein, 1991; Teger, 1980), business and finance (Baardsen & Grønhaug, 1990; Parayre, 1995; Staw & Ross, 1987; Švecová et al., 2012; Tamada & Tsai, 2014), health care (Hartman et al., 1991), marketing, sports (Keefer, 2015, 2019), tourism, (Wattanacharoensil & La-ornual, 2019) consumerism (Hartman et al., 1991), and decision-making (Garland & Newport, 1991; Hartman et al., 1991; Thaler, 1985; Whyte, 2019).

According to a meta-analysis by Roth, et al. (2015), sunk cost fallacy research generally shares a central concept in which resources have been spent and therefore, "costs are sunk" (p. 100). Out of this research, two main decision types used in studies to evaluate sunk costs have emerged, based on either (1) utilization decisions made with a single decision, or (2) based on progress over several steps.

Utilization Decisions. The key utilization decision studies (e.g., Arkes & Blume, 1985; Kahneman & Tversky, 1979), tend to evaluate sunk cost fallacy with single decision scenarios. In a single decision scenario, participants are presented with a fictitious situation in which they must make choices based upon an imagined role. For instance, choosing between a 50% chance to win a three-week tour of Europe, or a guaranteed one-week tour of England (Kahneman & Tversky, 1979a); assuming the role of a corporate finance manager and making investment decisions about projects (Staw, 1976); whether to spend more resources to complete an aerospace project (Garland, 1990); and choosing between a more or less costly vacation (Arkes & Blumer, 1985). In these examples, utilization decisions occur when participants are confronted with the choice between two equally attractive alternatives, and the decision-maker shifts preference to the sunk-cost alternative (Roth et al., 2015). In other words, people want to receive a perceived amount of value or use for their resources spent. Thaler (1980) stated that past decisions and expenditures influence current decisions, and that the rate or amount of use (i.e., utilization intensity; Roth, et al., 2015) is related to paying for something. Arkes and Blumer (1985) reported that there is a "greater tendency to continue an endeavor once an investment in money, effort, or time has been made" (p. 124).

Progress Decisions. Progress decision research, on the other hand, focuses on decisions made over an entire series of decisions as part of a broader course of action. Progress decisions "require a temporal element, including a specific beginning and end date" (Moon, 2001). A progress decision begins with an initial investment in a project and continues with additional choices about resource allocation thereafter (Roth, et al., 2015). Decision makers must choose to either persist or withdraw from their initially chosen path. For example, as a project continues, the decision-maker receives information that additional resources are required to continue the project. If the project is on a failing course, and the decision is made to persist, rather than withdraw, the decision-maker has presumably allowed historical sunk costs to influence the decision, and thus falls victim to the sunk cost fallacy.

In progress decisions, the sunk cost fallacy contributes to decision-making which often has a large-scale effect. For example, (Staw et al., 1997) analyzed historical data comprised of bad debt incurred over nine years by 132 banks to investigate how banks deal with the accumulation of problem loans. The authors found that tenured operational managers held on to failing loans much longer, increasing institutional losses because they failed to take adequate action. Following a turnover in management, these bad loans were rapidly addressed. The tenured managers exhibited behavior influenced by the sunk cost fallacy and did not cut their losses when it was financially responsible to do so.

As evidenced in this example, in progress decisions, the final outcome is the result of a multiple decisions, chained together over some period of time (Kanodia et al., 1989), in which a "decision-maker allocates additional resources to an initially chosen alternative, such that sunk costs increase the likelihood of further" resource allocation, escalating the commitment to that course of action (Roth et al., 2015, p. 100).

Escalation of Commitment: An Intersection of Sunk Costs and Project Completion

Escalation situations occur over time and through repeated "progress" decisions. Sunk costs "in the face of negative feedback about prior resource allocations," and "uncertainty surrounding the likelihood of goal attainment" influence decision making about whether to continue or withdraw (Brockner, 1992, p. 40). This results in an escalation of commitment, which occurs when decision-makers persist in a failing course of action, thus effectively increasing their resource allocation further (Brockner & Rubin, 1985; Staw, 1976). In short, the Escalation of commitment occurs when the effects of the Sunk Cost Fallacy are compounded when decision-makers "double down" on resource investment (Harvey & Victoravich, 2009, p. 761).

Along with sunk costs, another important contributor to the escalation of commitment is the project completion level. Garland and Conlon (1998), Conlon and Garland (1993), and Moon (2001) argue that many studies (Arkes & Blumer, 1985; Garland, 1990; Garland & Newport, 1991) confounded sunk costs with the amount or percentage of a project's completion. For example, "Motivation to achieve a goal increases as an individual gets closer to that goal" (Conlon & Garland, 1993, p. 403). Moon (2001) argues that high-completion levels interact cooperatively with sunk costs, resulting in increased psychological pressure to continue a project as the end nears. The variables magnify the effects of the other. For example, decision-makers should be more likely to choose to continue with a course of action that is nearing 90% completion, compared to a project at 10% which may be more likely to be abandoned. (Conlon & Garland, 1993; Garland, 1990; Garland & Conlon, 1998; Harvey & Victoravich, 2009; Moon, 2001). A historical example of the effects of project completion level can be seen in Ross and Staw's (1993) report on the temporal nature of escalation related to the Shoreham Nuclear Plant project where a "majority of the expenditures were allocated after the plant was thought to be 80% complete" (p. 111). Harvey and Victoravich (2009), and Moon (2001) argue that the sunk cost fallacy and project completion level exert a synergistic effect on decision-making, in that in the sunk cost fallacy influences decision makers to look back at historical costs, while the project completion level influences decision-makers to look forward. In addition, higher project completion levels appear to exaggerate the perception of certainty about the success of a project. Perhaps this is one reason why uncertainty plays a large role in withdrawal from a project with high sunk costs, but low completion. Interestingly, temporal factors and uncertainty reflect differences in an overall project goal and the short-term tasks required to complete the project. For example, Hsiaw (2018) conducted research in project goal setting and found that the "aggregate [project] goal becomes more attractive as early-stage uncertainty increases, whereas incremental goals become more attractive when later-stage uncertainty increases" (p.100).

Alternatively, Harvey and Victoravich (2009) argue that providing a viable, thus more certain, alternative option reduces the effects of project completion on escalation decisions. When an alternative is more certain (because costs, i.e., risks, are made more explicit), decision-makers tend to withdraw from the current course of action and switch to the alternative more often, which would be a reduction in the sunk cost fallacy. For example, Keil, Truex, and Mixon (1995) investigated the interaction of sunk costs and project completion in an information technology project The authors report that sunk costs and project completion level influenced decision-makers to continue to fund a project, but, when presented with an equivalent alternative and more certain course of action, this presentation mitigated the effect (meaning, people chose the alternative instead of staying with the project). That is, the alternative contained enough certainty that the effects of sunk costs were mitigated when decision-makers chose to forgo their previous investments for the alternative. In addition, Tan and Yates (1995) reviewed key decision-making theories and postulated that providing information certainty about the future return on resource investment (e.g. explicit estimates for return) also reduces the sunk cost fallacy. However, the authors explain that explicit estimates on future outcomes are not always available in the real world.

Resource Investment: Money, Time, and … Effort?

Arkes and Blumer (1985) proposed that the sunk cost fallacy resulted from the human tendency to continue with a specific strategy because of their prior investments, such as money, time, or effort. In other words, people fall victim to the fallacy because they feel they have invested too much to quit, and they do not want to be seen as wasteful. However, the authors did not specifically evaluate or define *effort* (e.g., whether physical or mental). Furthermore, research in the subsequent decades since Arkes and Blumer's foundational research demonstrates contradictory findings, particularly for time and effort sunk costs. (See Table 1 for a summary of key research).

Author	Resource Investment	Findings
Arkes & Blumer (1985)	Monetary Investments	Decision-makers "throw good money after bad," possibly because of social perceptions related to being irresponsible and/or wasteful
Banerjee, Chandrasekhar, and Srikant (2019)	Cognitive Effort on a task	Decision makers use cost as a reference point for desired compensation and *increase* efforts to meet performance goals
Cunha and Caldieraro (2009; 2010)	Cognitive Effort on a task	Effort: The value of and amount invested in a decision or choice *increases* with more cognitive demand
DeVoe & Pfeffer (2007a, 2007b)	Cognitive Effort on a task	Prior research mostly linked to monetary investments where effort is not independently measured
Heath (1995)	Time and Money	Invest *more* time to recover money
Soman (2001)	Time	Time has no effect unless represented by monetary equivalent
Tait, Miller Jr. (2019)	Money, time, and effort	Larger initial investments, particularly monetary, increase the occurrence of

		the Sunk Cost Fallacy over time and effort.
Zeelenberg and van Dijk (1997)	Time and effort	Time investments are sunk *more* than effort

Table 1. Prior Research Summary Table of Sunk Cost Fallacy variables and findings

To begin, Cunha and Caldieraro (2009; 2010) confirm the lack of focused research on behavioral investments such as effort and suggest that this may be the result of the difficulty in measuring effort, which is less quantitative than that of time or money. The authors further argue that most investments involve behavioral aspects which makes separating behavioral investments, such as effort, from monetary-based measurements difficult. In fact, much of the prior research has linked behavioral investments with monetary equivalents (DeVoe & Pfeffer, 2007a, 2007b). For example, Soman (2001) found that no effect of time investments are found unless they are represented by a monetary equivalent. However, Heath (1995) found a strange preference reversal when comparing time and money investments even when the two are considered to be equivalent. That is, to recover the sunk costs of time, people are more willing to invest money. Yet, to recover the sunk costs of money, people are more willing to invest time. On the other hand, Zeelenberg and van Dijk (1997) compared the effect of time and effort investments, and found that in situations in which the sunk cost fallacy occurred, behavioral investments resulted in lower overall sunk costs than investments of time. In other words, time was perceived as more valuable than behavioral investments. Finally, in a scenario-based procedure, Tait and Miller (2019) compared the effect of an initial high or low investment of money, time, and effort. The authors reported the Sunk Cost

Fallacy occurred more when initial investments were relatively large, with monetary investments having the greatest effect over time and effort.

Cunha and Caldieraro (2009; 2010) attempted to develop a model for evaluating behavioral investments that exclude money and that better operate under effort-justification factors: the perceived utility of a choice increases as effort increases. In other words, the Behavior Investment Sunk Cost (BISC) models effort (i.e., behavioral investment) relative to opportunity costs of an alternative and the perceived value. Although Otto (2010) reported he could not replicate Cunha and Caldieraro's (2009) research, the authors countered in their 2010 publication that their model and previously unpublished research supported their claims. The 2010 publication contained experiments in which participants used a Likert Scale to rate products compared to a target product rank or made value estimations based on a small number of product attributes (low effort) versus many attributes (high effort). The target product ranks were presented in text (e.g., seven, five, three) in the high effort condition and integers (e.g., 7, 5, 3) in the low effort condition. The time to evaluate product attributes was the objective measure of cognitive effort, with longer decision times interpreted as requiring greater mental effort. The authors proposed the effort-justification mechanism as an underlying factor in behavioral sunk-costs effects (Aronson & Mills, 1959; Axsom, 1989). The effort-justification mechanism suggests that people experience cognitive dissonance when performing cognitively demanding tasks and compensate by assigning value to the task as a function of effort. That is, when a task is mentally challenging, people compensate by increasing both the value and effort put toward the task. Cunha and Caldieraro found that participants were less likely to switch from a product that required a higher effort evaluation, (i.e., those with more attributes to be rated).

Banerjee, Chandrasekhar and Srikant (2019) investigated the effects of cognitive effort in sunk cost fallacy. In their study, participants performed simple cognitive tasks (counting red circles) in two phases. Participants could complete the first phase and receive payment or continue to the second phase to receive additional compensation based on performance. It was assumed that more effort resulted in better performance. In the control condition, participants could keep payments from both phases. In the treatment condition, participants would forgo their payment from phase one, if they decided to continue to phase two. Results indicated that participants in the treatment condition who continued to phase two performed significantly better (i.e., exhibited more effort = higher sunk cost) than those who chose to quit after phase one. The increased effort as a sunk resource increased in the final blocks of phase two. The authors argue that this demonstrates a persistence of the effects of the sunk cost fallacy. That is, decision makers use cost as a reference point for desired compensation and increase efforts to meet performance goals. However, it is difficult to determine in this study whether the improved performance was due solely to increased effort, or other factors such as training effects and the higher perceived value of non-monetary rewards.

In social contexts, Hrgović, (2018) found that maintaining an interpersonal relationship requires *less* cognitive effort than terminating it. In the study, participants decided whether to continue investing into an unprofitable business endeavor or interpersonal relationship. The time utilized to decide to continue was the objective measure of cognitive effort, with longer decision times interpreted as requiring greater mental effort. Decision-makers took longer to terminate highly interpersonal relationships (e.g., romantic, friend or sibling) than the business venture.

In summary, people prefer to avoid losses, when given a choice. When prior investments are made, people tend to avoid discontinuing a task to avoid losing the investment. These investments may be money, effort, or time. Progress decisions are complex and chained together over time, versus utilization decisions that are more related to single decision scenarios. Uncertainty plays a role in whether people choose to persist or withdraw from a task because decision-makers are averse to both loss and ambiguous outcomes. In addition, the level of project completion (e.g., 20%, 80%) influences the decision to switch to an alternative as people are less likely to withdraw when a project is closer to completion.

However, from a review of the research literature on decision-making biases, it appears that there is disagreement regarding the context and effects of uncertainty, project completion level and the types of resource investment that underly the effects of the sunk cost fallacy on decision-making. Some report that (1) providing more certainty about prospects reduces the effects, and (2) project completion levels are inseparably linked to sunk costs in progress decisions. Furthermore, mental effort has not been a focus of research, and has not been adequately studies to make definitive conclusions that effort is an equally effective investment to that of money and time. Finally, from this review it is evident that many studies do not examine progress decisions in an experimental context, but rather pull from historical accounts. In short, single-decision scenarios and historical accounts do not amount to reliable evidence that can be applied in a complex cyber environment where robust defenses are imperative for organizational security. We next present our experiments in which certainty, project completion, and mental effort as an invested resource are studied within a progress decision platform with interactive tasks.

CHAPTER 3

EXPERIMENTS

In a cyber realm, attackers who invest a lot of resources in the attack process may tend to consider historical costs in assessing the value of a future outcome and the decision to continue in the attack. We believe that uncertainty impacts decision-making, and as cyber attackers invest resources and the project completion point increases, discontinuing or withdrawing from a task may be psychologically difficult. In addition, the activities of malicious actors require, in large part, intense mental effort. We anticipated that the likelihood of making an irrational decision is significantly increased by an attacker's investments as they advance further toward their goal (e.g., Cyber kill-chain, Hutchins et al., 2011). Therefore, we approached our investigation of the sunk cost fallacy with two experiments to address our research questions.

Specifically, within the cyber domain:

Research Question 1. *Does uncertainty effect the sunk cost fallacy?*

Research Question 2. *Does the project completion level effect the sunk cost fallacy?*

Research Question 3. *Does project difficulty effect the sunk cost fallacy?*

Research Question 4. *Does the combination of uncertainty and project completion level effect the sunk cost fallacy?*

Research Question 5. *Does the combination of uncertainty and project difficulty effect the sunk cost fallacy?*

We sought to understand, within a cyber environment, if the foundational research and theory could be adequately tested in an interactive progress decision platform, and what variables may influence sunk cost in these progress tasks. For this dissertation, to understand the sunk cost fallacy in progress decision scenarios related to cyber security, two experiments were conducted that utilized a new (created as part of an ongoing program) experimental paradigm called *CYPHER*. The CYPHER platform was designed and developed in collaboration with the Department of Defense for this project and with the goals of evaluating sunk cost in mind. The platform is also intended to accommodate a wide variety of experimental manipulations in future projects to examine other biases. The following sections present the two experiments conducted for the current project. The reader will recall that a second platform, Attack Surface, built upon the findings from CYPHER, with increased cyber fidelity is underway and will further our inquiry into best practices for eliciting the Sunk Cost Fallacy in cyber attackers. Furthermore, in this project we are primarily focused on attacker behavior. While the narrative in CYPHER places the participant in a defender role, the tasks are analogous to those performed by an adversary. That is, participants are asked to decrypt passwords to advance through abstracted data servers in the pursuit of accomplishing a goal. Future work will examine the effects of assigned role on behavior (e.g., defend versus attack).

Experiment 1: Research Design

The Cypher experiments employed a 2x2 factorial design with randomized assignment to groups. In experiment 1, we evaluated the effects of uncertainty and project completion level on the elicitation of the sunk cost fallacy. In the following sections, we report the experimental design, procedure, and material, including the research questions, hypotheses, and variables.

In a simulated cyber environment, participants assumed the role of a cyber defender and solve encrypted passphrases to catch a cyber attacker (see Figure 4 for task introduction text). Participants had a limited number of resources (time, in-game currency) to help solve encrypted passphrases (e.g., cyphers). Using a provided alphanumeric table and key, participants solved *seven p*assphrases on one of two available portals (Server A or Server B) (see Figure 7). A portal represented a data server. To begin, participants were given a choice between two portals (see Figure 5). Next, after correctly solving cyphers, an opportunity to change portals was displayed (see Figure 6) Once the choice was made to either stay on the current portal, or switch to the alternate, participants were not able to return to the previous portal. Passphrases varied in length; some were long (up to 11 characters), while others were short (5 characters) (see Table 2 for an example of cyphers, solution, and key; Appendix K. for complete list.)

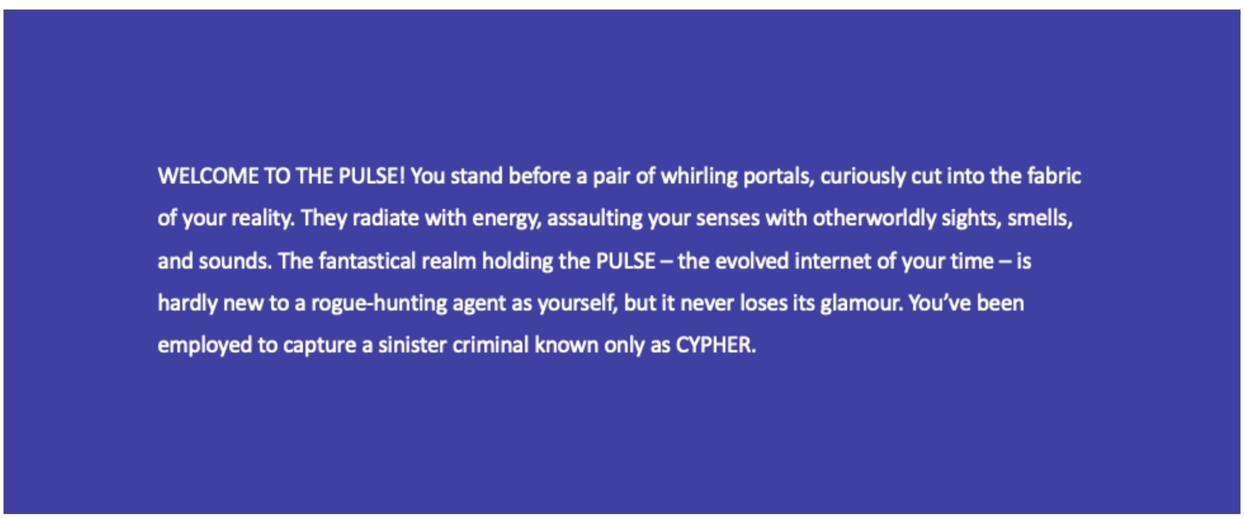

Figure 4. Task Introduction screen

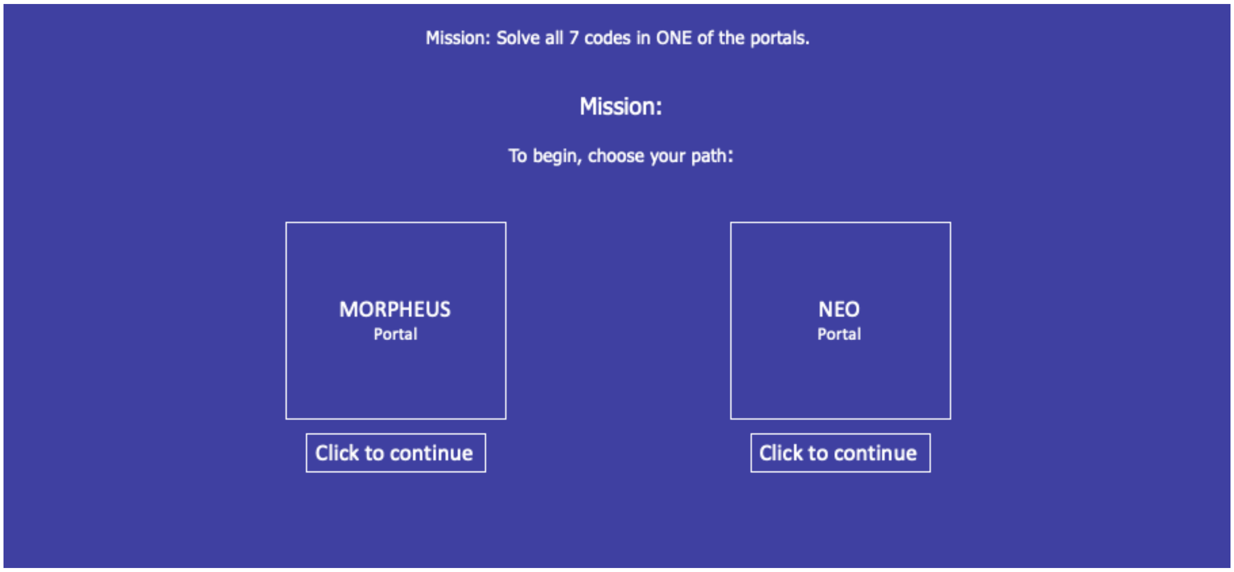

Figure 5. Starting portal choices.

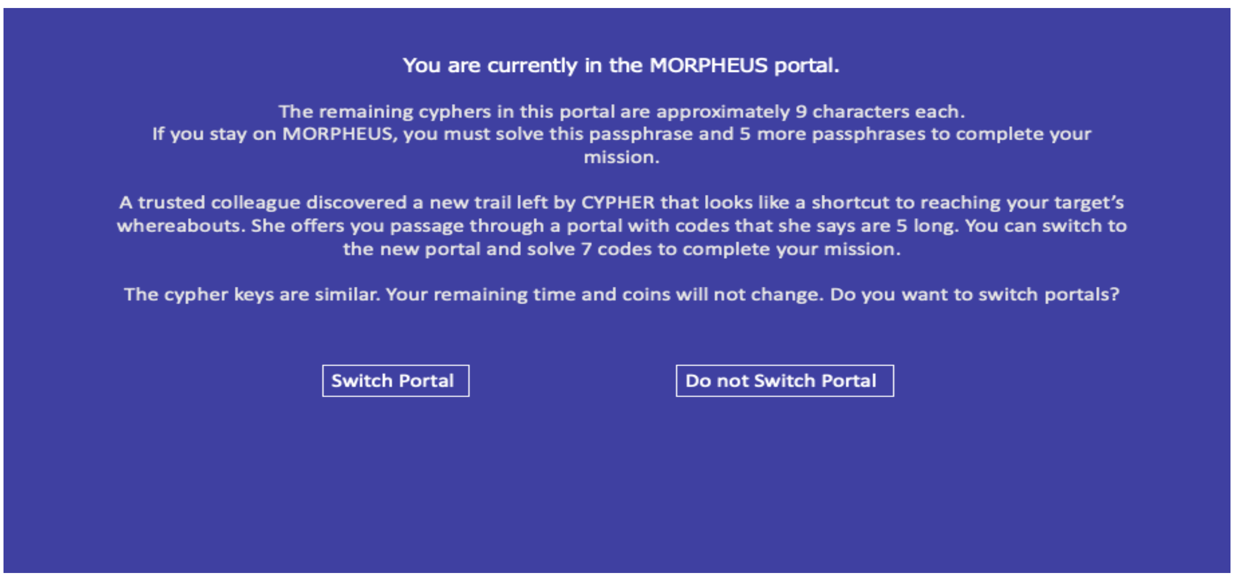

Figure 6. Opportunity to switch portals.

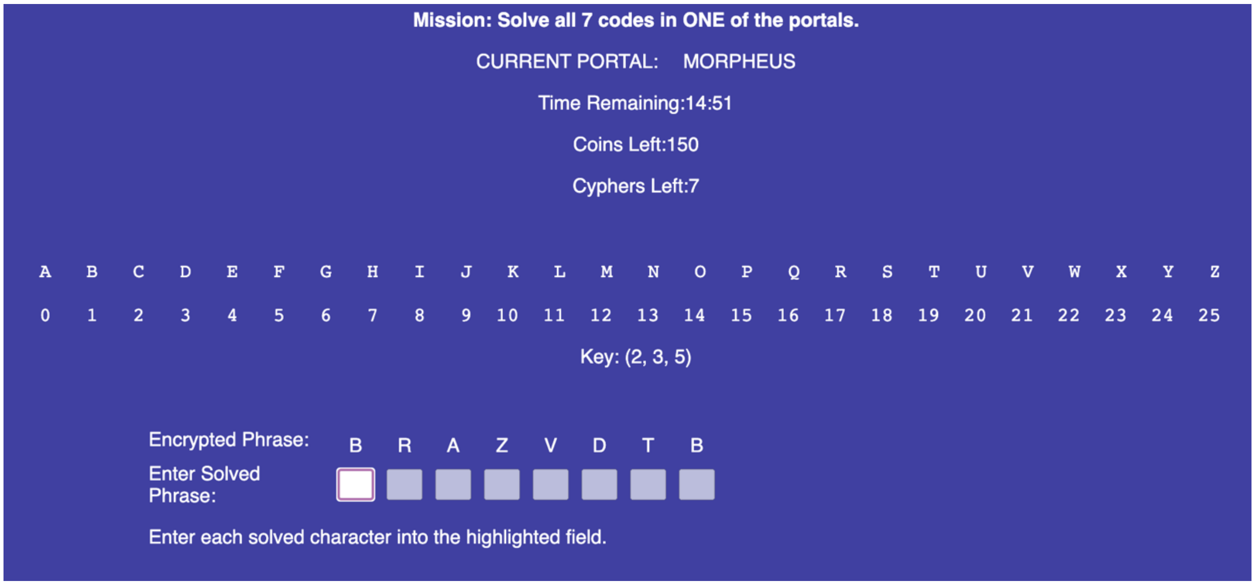

Figure 7. Example of cypher in the Performance Trial.

Cypher	Solution	Key	Length/ Coin Cost
cwurm	atppj	2,3,5	5
kxbiefo	duzbbdh	7,3,2	7
apoqoejly	yklojbhgv	2,5,3	9

Table 2. Example of cyphers, solutions, and keys.

Solving and Encrypted Password with an Alphanumeric Table. The alphanumeric table (e.g. cryptex) in the CYPHER paradigm uses a Gronsfeld Cipher, a variant of the Vigenére Cipher to encrypt and decrypt with polyalphabetic substitution (de Leeuw & Bergstra, 2007). The Gronsfeld Cipher uses integers for the key, instead of letters. The Gronsfeld method approaches multi-shift encryption. For example, the encrypted text given is *dirlfr*, with key 102410, and thus decrypts to *cipher*. See Figure 8 below for an overview of an alphanumeric table, integer key, encrypted and solved passphrase.

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

Key: 9, 5 , 8

Encrypted passphrase: B I M X G D M O I I M Y T K B

Solved passphrase: S D E O B V D J A Z H Q K F T

Figure 8. *Gronsfeld Cipher. The alphanumeric table is shown at the top of the graphic, with the key [9, 5, 8] centered below. The table and key are used to solve the encrypted passphrase. Solved passphrase shown at the bottom center.*

Participants were given a bank of resources (coins) as well as a time limit (15 minutes). Each character entered cost 1 coin and only one letter could be entered at a time sequentially; skipping around in the phrase was not allowed. Incorrect entries cost 2 coins each. Participants were instructed to only use as many resources as absolutely needed to complete the mission. An on-screen count down timer and bank kept track of remaining time and coins.

Each participant completed one session, consisting of two performance trials. A session included (1) task instruction and storyline, (2) task demonstration (see Figure 9), (3) practice trial (see Figure 10), (4) two performance trials with 1 opportunity to switch in each, (5) an inter-trial survey, and (6) a post-session survey.

Training Phase. The first task in each experiment was the training phase in which participants viewed a demonstration, and then practiced solving one passphrase prior to moving to the performance phase.

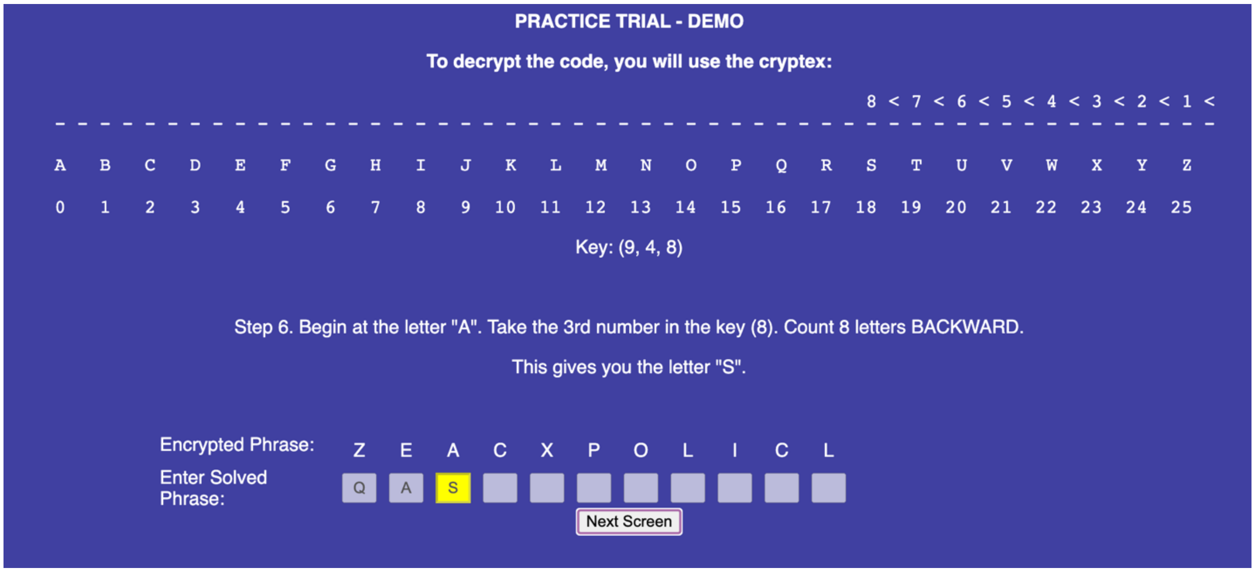

Figure 9. *Task Demonstration*

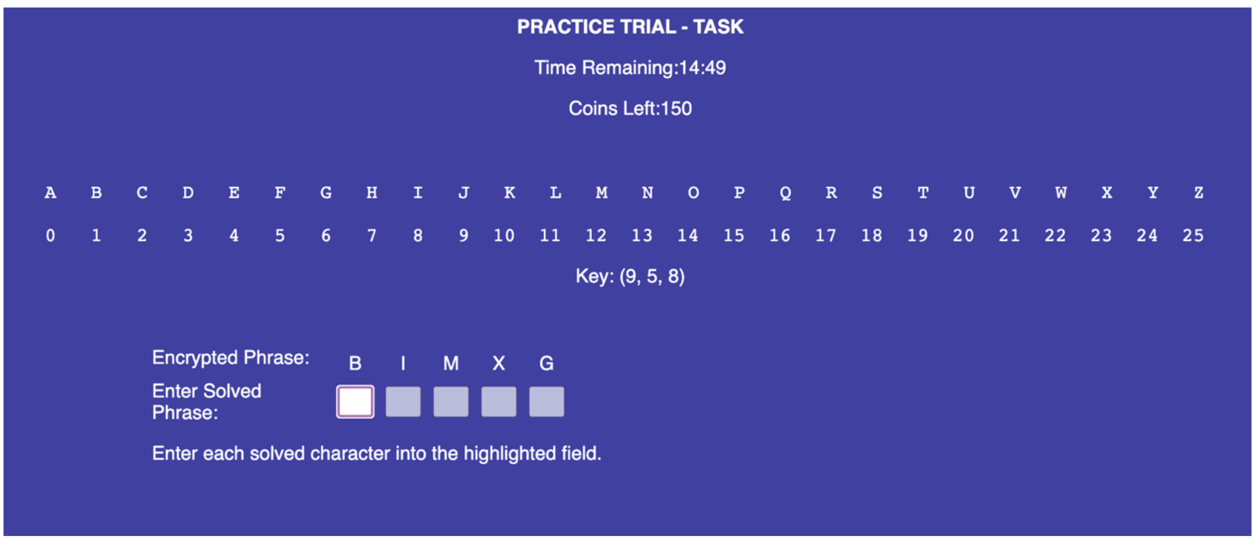

Figure 10. Task Practice Trial

Surveys and Measures. In addition to the CYPHER tasks, several questionnaires were presented to measure various aspects of participants' decision-making process. The following sections provide justification for these surveys along with anticipated interpretation.

Inter-trial Questionnaire. To capture participants' thoughts about the task, a short, four-question survey was presented between trial 1 and 2. The intent of these multiple-choice questions was to gather qualitative data that provided a richer understanding of the task decision-making process (e.g., How difficult would you say this task is?). Although not a key variable in the experiments, these data were interpreted alongside measures of the sunk cost fallacy (see Appendix B).

Post-Session Task Questionnaire. The Task Questionnaire contained seven questions to evaluate participants' (1) intent and motivation for participating in this experiment (e.g., Why did you choose to participate in this experiment?), (2) decision-making and reasoning for choices and (e.g., How did you choose to start on one portal, over the other?), (3) general risk-taking behavior (e.g., Do you ever play the lottery?). Participant statements describing decision-making processes are presented alongside measures of the sunk cost fallacy (see Appendix C).

Post-Session Chance Questionnaire (Kahneman & Tversky, 1979). Directly related to the sunk cost fallacy, this questionnaire measured the effects of certainty with a non-monetary outcome, and attitudes toward risk or chance. For example, participants were asked to choose between a 5% chance to win a 3 week, all expenses paid vacation to 3 locations of choice or a 10% chance to win a 1 week, all expenses paid vacation to 1 location of choice. The analysis and interpretation of these data followed the general approach found in Kahneman and Tversky's original work, reflecting decision-making and uncertainty and are presented alongside measures of the sunk cost fallacy (see Appendix D).

Post-session Intolerance to Uncertainty Scale (IUS-12, Short Form). The Intolerance to Uncertainty Scale (IUS-12) – Short Form (Carleton, Norton, & Asmundson, 2007) was adapted from the original 27-item IUS form (Freestone, Rhéaume, Letarte, Dugas, & Ladoucer, 1997) to measure intolerance of uncertainty and is conceptually linked to ambiguity. The IUS-12 was reduced from the original 27 item scale to 12 items. A meta-analysis was conducted by Fergus (2013) and reported that the reduced scale compared to original, maintains internal consistency and high correlation. The IUS-12 assesses two factors: (1) cognitive anxiety (prospective anxiety), and (2) behavioral anxiety (inhibitory anxiety). These data were interpreted to reflect the individual differences in participants' decision-making behavior and presented alongside measures of the sunk cost fallacy (see Appendix E).

Participants. In Experiment 1, 388 participants were randomly assigned to one of four conditions based upon the certain or uncertain manipulation and the project completion level as an early or late presentation of the alternative (i.e., portal switch opportunity). The four conditions were: Early-Certain (control), Early-Uncertain, Late-Certain, and Late-Uncertain.

Certainty was manipulated by presenting certain or uncertain information about the alternate portal (switch message). For example, an uncertain message presented information about the cyphers as an estimate, whereas a certain message presented information as an exact value (see Figures 11 and 12).

Uncertain Information – *estimated range* code length

"An **informant** picked up on another trail left by CYPHER that **may be** a shortcut to reaching your target's whereabouts. She offers you passage through a portal with codes that **she claims** are between **[7-10]** characters long. You can switch to the new portal and solve **[5]** codes to complete your mission. Do you want to switch portals?"

Figure 11. Uncertain condition – Switch Portal message.

Certain Information – *exact* code length

"A **trusted colleague** discovered a new trail left by CYPHER that **looks like** a shortcut to reaching your target's whereabouts. She offers you passage through a portal with codes that **she says** are **(5)** characters long. You can switch to the new portal and solve **(7)** cyphers to complete your mission. Do you want to switch portals?"

Figure 12. Certain condition - Switch portal message.

The project completion level was manipulated by the timing of the switch message presentation Early conditions received a switch notice on the second character entry of the second cypher. Late conditions received a switch notice on the first character of the third cypher (see Figure 13). The interval was designed to ensure resource conservation when switching portals (Appendix N).

EARLY CONDITION			
1st Cypher		**2nd Cypher**	
encrypted	BIMXG	encrypted	CWURM
solution	SDEOB	solution	AT_ _ _

LATE CONTITION					
1st Cypher		**2nd Cypher**		**3rd Cypher**	
encrypted	BIMXG	encrypted	CWURM	encrypted	KXBIEFO
solution	SDEOB	solution	ATPPJ	solution	D_ _ _ _ _

Figure 13. Early and Late presentation: Early conditions - portal switch message was presented following the correct entry of the 2nd character in the 2nd cypher. Late

conditions – portal switch message was presented following the correct entry of the 1st character of the 3rd cypher.

CYPHER: comparing portals at switch

Research on the effects and implementation of examining uncertainty in the Sunk Cost Fallacy are mixed. Thus, in this project, to test the existing theory in a cyber environment, the information presented at the critical decision-making point (switch opportunity) contained a two-part message to address the current portal and the alternative.

At the switch message presentation, participants in either the certain or uncertain conditions were provided with the knowledge to *clearly* understand the outcome for either staying on the current portal or switching to the alternate. In other words, the manipulation of certainty in CYPHER was designed to be *explicitly clear*. Participants were provided with number of characters in each code, and the number of codes to be solved to finish the task. In the certain condition, the communication related the exact parameters of the alternate portal whereas the uncertain condition presented estimated parameters. All messages contained a two-part comparison, presented in each condition between the (*stay)* Current or *(switch)* Alternate portal message. Specifically, the Current portal contained 5 more codes to be solved, each code approximately 9 characters in length. The alternate portal contained 7 more codes to be solved, each code 5 characters long. See below.

<u>(Stay) Current Portal Information</u>

1. You are currently in the MORPHEUS portal.
2. … remaining cypher in this portal are approximately 9 characters each.
3. If you stay on MORPHEUS, you must solve this passphrase and 5 more.

(Switch) Alternate Portal Information

1. … passage through a (alternate) portal with codes . . . 5 (characters) long.
2. … switch … and solve 7 codes to complete your mission.

Recruitment. This research was conducted with the approval of the Institutional Review Board at Arizona State University (Study 00010523), and the Department of the Defense. Due to COVID-19, in-person research recruitment through the Arizona State University SONA system was restricted. Amazon MTurk (AMT), Human Intelligence Tasks (HIT) was used exclusively for recruitment. AMT is an online crowdsourcing platform, which requires users to have an established account and meet the qualifications for the survey, including an informed consent. AMT is a reliable method for collecting a broad range of data, and participant performance has been shown to be equivalent to, or oft times better, than undergraduate college students (Anson, 2018; Hauser & Schwarz, 2016).

Inclusion and Exclusion Criteria. For the present study, participant qualifications included a) live in the United States, b) 18 years of age or older, c) fluent in the English language, d) understand how to use basic computer devices (keyboard and mouse), e) have access to a computer and internet, f) be able to sit in front of a computer monitor for the full length of the study, approximately 1 hour in length, g) have normal or corrected to normal vision, and h) only complete the study once. Participants in the Mturk subject pool were screened as part of the HIT service (Reside within the United States, completed at least 50 HITs with a 95% or better approval rate).

Experiment 1: Research Questions and Hypotheses

Research Question 1. Does uncertainty effect the sunk cost fallacy?

Hypothesis 1. The sunk cost fallacy occurs more in uncertain conditions.

Uncertainty plays a role in the decision to persist or withdraw from a task. Those in the uncertain condition will switch less from an initially chosen project (signaling the sunk cost fallacy) than those in the certain condition. Certainty was manipulated by presenting certain or uncertain information about the alternate portal (switch message). For example, an uncertain message presented information about the cyphers as an estimate, whereas a certain message presented information as an exact value. The independent variable was certainty, with two levels: certain and uncertain. The dependent variable, portal switch, was binomial (yes/no).

Research Question 2. Does the project completion level effect the sunk cost fallacy?

Hypothesis 2. The sunk cost fallacy occurs more when a project is closer to completion.

Project completion levels contribute to the decision to persist or withdraw from a task. Participants in the late condition will switch less (signaling the sunk cost fallacy) than in trials with an early interval. The early interval signifies less completion, whereas the late interval signifies more completion. The project completion level was manipulated by the timing of the switch message presentation. Early conditions received a switch notice on the second character entry of the second cypher. Late conditions received a switch notice on the first character of the third cypher. Participants were randomly assigned to one of two conditions based upon the timing interval of the switch message. The independent variable was project completion, with two levels: Early and Late. The dependent variable, portal switch, is binomial (yes/no).

Research Question 4. Does the combination of uncertainty and project completion level effect the sunk cost fallacy?

Hypothesis 4. The sunk cost fallacy occurs more in uncertain conditions when a project is closer to completion.

Uncertainty and the project completion level cooperative (Moon, 2001) or magnify their effects, in the decision to persist or withdraw from a task. Those in the Late-Uncertain condition will switch less and spend more resources than those in the Late-Certain and Early conditions.

Participants were randomly assigned to one of four conditions based upon (1) the certain or uncertain manipulation and (2) the timing of the switch message presentation. The four conditions were: (1) Early-Certain (control), (2) Early-Uncertain, (3) Late-Certain, and (4) Late-Uncertain. The dependent variables included portal switch choices, and resources (time and coins). Resources were measured at two intervals: first the time and coins spent prior to the decision was made to stay or switch, and second, the time to complete the trial.

Experiment 1: Data Collection

Data collection for Experiment 1 ran from July 14, 2021, through August 4, 2021, on Amazon MTurk. The HIT approval rate for all tasks was set to be greater than or equal to 95%, with the number of approved HITs set at greater than 50; participants were in the United States. The experiment was posted on Mturk in an iterative process, one condition at a time. Once a HIT was closed, the data was reviewed and removed per the criterion described below. This process balanced quality control with the ability to ensure each participant completed only one experiment.

A total of 6 HITs were posted, N = 875, which, after the data was prepared, n = 388 (Table 3). Participants by gender: Male, N = 244, Females N = 144, Other, N = 1, Age, *M* = 36.96, SD 10.31, Min = 20, Max 77. The following section describes the data preparation process.

Experiment	**Condition**	**HIT Request n**	**Rejected (M-Turk) n**	**Post M-Turk Removal n**	**Retained n**	**Combined HIT n**
Cypher 1	Early-Certain	175	-	88	87	**95**
		25	-	17	8	
	Late-Certain	200	-	130	70	**96**
		100	53	21	26	
	Early-Uncertain (control)	200	-	101	99	**99**
	Late-Uncertain	175	-	77	98	**98**
	Total	875	53	434		**388**

Table 3. Data collection and preparation results

Experiment 1: Data Preparation

The data collection was rapid, however, due to the data quality, an extensive review and removal process was required. As data collection progressed, it became apparent that participants were attempting to circumvent the requirements of the task (see Table 4 and Removal Criteria below).

Mturk Rejected. Data were rejected prior to the close of the HIT. Participants were not compensated for their HIT assignment. Rejection began in Cypher #1 (7/27/2021), LC condition. Removed data in all other conditions in Cypher #1 were post-removed. Removed data in all conditions in Cypher #2 were rejected from Mturk, followed by the post-removal criteria described below.

Post-HIT removal. These data were removed from the log after the HIT closed. Thus, these participants were compensated for their HIT assignment. Oft times, participant data were removed due to both types of removal criteria below.

Removal Criteria 1. Event Log. Participants who clearly did not attempt to complete the task were removed (e.g., "key mashing). These participants entered incorrect characters until resources were depleted (coins and time ran out).

Removal Criteria 2. Survey Log. Participants who clearly did not read, comprehend, or otherwise appropriately respond to questions (e.g., duplicate responses). For example, the response appeared to have copied arbitrary text from another source (see Table 4), or the prompt question was copy and pasted into the response field (see Table 4.1).

Prompt Question	Why did you choose to stay?
Participant Response	"… sides offering students information and helpful examples, we must show ... "

Table 4. Examples of removed data.

Prompt Question	How did you choose which portal to start on? List any details or thoughts you had, in order.
Participant Response	"List any details or thoughts you had in order."

Table 4.1. Examples of removed data.

Removal Criteria 3. Outliers. Exploratory Analyses. Data that fell beyond 3 SD were removed prior to each analysis.

Experiment 1: Analyses

To evaluate the influence of uncertainty, project completion on portal switch behavior, chi-square tests of independence were performed to examine the relationship between the independent variables, with rates of switching to a new portal (a binomial, dependent variable) in each trial. In addition, we conducted preliminary, exploratory analyses to further investigate resource utilization of time (MANOVA, Bonferroni correction) and coins (Kruskal-Wallis H test, Benjamini Hochberg correction), (see Appendix J).

Crosstabulation. A crosstabulation for Experiment 1 demonstrates that overall, irrespective of condition, 159 participants *always chose to stay* on the starting portal compared to 118 who *always switched* (see Table 5). Participants who chose to change their strategy (e.g., stay in trial 1, switch in trial 2) were nearly equal. These results demonstrate that the effects of the Sunk Cost Fallacy can be measured within a progress decision, task-oriented experiment.

Experiment 1: Trial 1 Switch * Trial 2 Switch Crosstabulation

	T2_Switch		
	Stay	Switch	Total

		n	%	n	%	n	%
T1_Switch	Stay	159	75.7%	60	33.7%	219	56.4%
	Switch	51	24.3%	118	66.3%	169	43.6%
Total		210	100.0%	178	100.0%	388	100.0%

Table 5. Crosstabulation, Experiment 1. Trial 1 and 2.

A paired samples t-test was conducted between those who stayed or switched in both trials. There was a significant difference between those who always stayed (M = 14.45, SD = 4.46) and those who always switched (M = 10.73, SD = 2.83), $t(10) = 2.17$, $p = .03$; switched on the first trial → stayed on the second trial (M = 4.64, SD = 2.25) compared to stay → switch (M = 5.45, SD = 2.25), $t(10) = 2.17$, $p = .03$; always stayed (M = 14.45, SD = 4.46) compared to stay → switch (M = 10.09, SD = 2.70), t(10) = 3.03, p = .006. There was no significant difference between those who always switched (M = 10.73, SD = 2.83) compared to those who stay → switch (M = 10.09, SD = 2.70, t(10) = .57, p = .29

Experiment 1: Trial 1 Results

Certain vs. Uncertain by Trial. To evaluate the main effects of uncertainty (H1) on portal switch behavior in Trial 1, chi-square tests of independence were performed to examine the relationships between the independent variables with rate of switching to a new portal. In trial 1, the proportion of portal switching behavior did not significantly differ between the Certain and Uncertain conditions, χ^2 (1, N = 388) = 0.002, p = 0.968.

Early vs. Late by Trial. To evaluate the main effects of project completion (H2) on portal switch behavior in Trial 1, chi-square tests of independence were performed to examine the relationships between the independent variables with rate of switching to a new portal. In trial 1, participants in the Late condition were significantly less likely to switch to the new portal, χ^2 (1, N = 388) = 4.623, p = 0.032 than the Early condition. These results support H2 and suggests the late switch message interval (i.e., late project completion level) elicited the sunk cost fallacy**.** The proportion of participants in the Late condition was 62%.

Cooperative (Magnification) Effects by Trial. To evaluate the comparison of the cooperative or magnifying effect of the independent variables (uncertainty and project completion) on portal switch behavior (H4), chi-square tests of independence were performed to example the relationship between the independent variables with the rate of switching to a new portal. While we expected Late-Uncertain condition to switch less than those in the Late-Certain and Early conditions, in trial 1, participants in the Early-Uncertain condition (EU) instead were significantly less likely to switch to the new portal than those in the Late-Uncertain condition, χ^2 (1, N = 388) = 3.80, p = .05. All other results were not significant. These results are contrary to H4. The proportion of participants in the Late-Certain condition who switched was 60%.

Experiment 1: Trial 2 Results

Hypothesis 1. The sunk cost fallacy occurs more in uncertain conditions. Participants in the Uncertain condition will succumb to the sunk cost fallacy (continue by staying, rather than switching) more than those in the certain condition.

Certain vs. Uncertain by Trial - Chi-Square. In trial 2, the proportion of portal switching behavior was significantly less in the Uncertain condition compared to the Certain condition, χ^2 (1, N = 388) = 6.09, p = 0.014. These results support **H1,** suggesting that uncertainty elicited the sunk cost fallacy. The proportion of participants in the Certain condition was 60%.

Hypothesis 2. The sunk cost fallacy occurs more when a project is closer to completion. Project completion levels contribute to the decision to persist or withdraw from a task. Participants should succumb to the sunk cost fallacy more (stay more often) in trials with later (higher completion) switch messages.

Early vs. Late by Trial. In trial 2, the proportion of portal switching behavior did not significantly differ between participants in the early versus late condition, χ^2 (1, N = 388) = 0.508, p = 0.476.

Hypothesis 4. The sunk cost fallacy occurs more in uncertain conditions when a project is closer to completion. Uncertainty and the project completion level cooperative (Moon, 2001) or magnify their effects, in the decision to persist or withdraw from a task. Those in the Late-Uncertain condition will switch less compared to the other conditions.

Cooperative (Magnification) Effects by Trial – Chi-Square. In trial 2, participants in the Early-Uncertain condition (EU) were significantly less likely to switch to the new portal than those in the Late-Certain condition, χ^2 (1, N = 388) = 5.02, p = .03. These results are contrary to **H4**. The proportion of participants in the Late-Certain condition was 61%. All other results were not significant.

Experiment 1: Survey Results

In addition to the CYPHER tasks, several questionnaires were presented to measure various aspects of participants' decision-making process. Although not key variables in the experiments, we provide a descriptive analysis interpreted alongside measures of the sunk cost fallacy. These results provide a richer insight and reveal individual differences in perceptions of chance and uncertainty. For our analysis, we provide proportions for the multiple-choice sections (Inter-Trial Survey and Chance Questionnaire), and Likert scale (Intolerance to Uncertainty Scale), as well as examples of participant statements (Post-Session Survey) regarding the experimental tasks.

Inter-Trial Survey. The results from the multiple-choice questions (“*Did you enjoy this task?”, “How difficult would you say this task is?”,* “*Why did you stay/switch portals?”*) were aggregated, and response proportions are provided in Table 6), (Appendix J see for proportions by condition).

In summary, most participants reported enjoying the experiment, found that solving the cyphers was moderately easy, and switched because they believed it would be faster. Switching portals because it was perceived as faster aligns with the Mturk subject pool (M-turkers are motivated to complete tasks quickly to ensure they are making money and being effective). That is, regardless of whether the cypher required more mental effort or not, participants tended toward a strategy that was perceived to be faster.

Did enjoy?	%	How difficult?	%	Why switch?	%
no	20%	easy	27%	faster	61%
yes	79%	moderately easy	57%	easier	35%
indifferent	15%	moderately hard	15%	bored	1%
don't know	1%	hard	1%	don't know	0%
other	0%	other	0%	other	3%

Table 6. Inter-Trial Survey.

Post Session Survey. The post-session survey contained multiple-choice, free response and Likert-scale questions. We next present analyses pertaining to our research questions.

Task Related Questions. This section of the post-session survey contained free-response questions regarding decision-making and task performance in the experiment. We evaluated and present relevant examples specifically related to our research questions. Future work will include a qualitative analysis of the complete set of data (see Tables 7 – 9 for response examples). Statements are direct quotes from the survey.

From our analysis, when reporting switch or stay decisions, five general themes emerged (1) those who were influenced by the sunk cost fallacy, (*"I don't like quitting. So when I got one wrong, I did not feel compelled to try the other side…")*, (2) those who understood the comparison between the two portals, either performing quick mental math (*"I chose to switch because I calculated that, even though I would have to start over, I would save time overall by having to decrypt fewer letters overall."*), or accepted the switch message prompt that stated the alternate portal contained shorter cyphers (*"based on the suggestion from the boss…"*), (3) those who seemed to choose based upon perceived performance ("*I was going very slow at first and when I switched over I seemed to go much faster."*), (4) storyline influence (To catch the thief, "*I switched the first time and it didn't work"*), or (5) personal motivation *("…*staying on one path/task feels more satisfying."*).*

Participants who reported they stayed on the starting portal.

1. *If you ever chose to* ***stay*** *on the current server when given the choice to switch, how/why did you make that decision? List any details or thoughts you had in order.*

Example Response 1	"I don't like quitting. So when I got one wrong, I did not feel compelled to try the other side…"
Example Response 2	"I thought it would be faster, plus I always finish what I start."
Example Response 3	"I chose to stay regardless of what the text said because staying on one path/task feels more satisfying."
Example Response 4	"Honestly, I didn't even really read the message..."
Example Response 5	"I thought that I'd already completed a cipher or two on the current server and would need to start over if I switched."
Example Response 6	"I decided to stay because I felt there was too much uncertainty associated with switching."

Table 7. Participants who stayed on the starting portal.

Participants who reported they switched from the starting to the alternate portal.

2. *If you ever chose to* ***switch*** *to the other server during this experiment, how/why did you make that decision? List any details or thoughts you had in order.*

Example Response 1	"I never stayed; switching was faster."
Example Response 2	

	"I decided the alternative sounded easier and faster."
Example Response 3	"Only have to crack the rest of the 5 instead of 7."
Example Response 4	"I chose to switch because I calculated that, even though I would have to start over, I would save time overall by having to decrypt fewer letters overall."
Example Response 5	"…based on the suggestion from the boss…"
Example Response 6	"i switched because it was a shorter task."

Table 8. Participants who switched from the starting to the alternative.

In response to the two questions above, participants also reported if they changed switching strategy between trial 1 and 2.

Example Response 1	"Curious what was the other server."
Example Response 2	"I decided to stay to see how it compared to swapping…[switch]I wanted to see if the game was steering me the right way"
Example Response 3	"…I chose to stay on the current server in the second round because I had already completed 2 codes and didn't want to start over at 7."
Example Response 4	"I just switched on the second round out of curiosity. On the first one I stayed on the same one because it was working well for me."

Example Response 5	"I was going very slow at first and when I switched over I seemed to go much faster."
Example Response 6	"I chose to switch based on my experience with the harder task when I chose to stay previously."

Table 9. Participants who changed switch strategy.

Prompt Question. *Do you know modular arithmetic?*

Most participants did not have a working knowledge of modular arithmetic (74 %) (see Tables 10, 11 below, Appendix M for proportions split by condition). Participants skilled in this math technique would make solving the cyphers easier, although knowing it was not necessary to complete the tasks. This metric provided information about switching behavior. For example, if a large group of participants knew and often used modular arithmetic, this could explain resource usage, particularly the time spent from the start of the trial until the switch opportunity, and overall time to complete the trial. Using modular arithmetic would allow participants to use a formula to quickly solve the cypher, saving time and possibly coins spent on errors made. Otherwise, participants followed the experiment instructions to compare a character in the passphrase to the alphanumeric table, then using the integer keys to count backward to find the deciphered character. Since most did not report proficiency, we can assume that a command of modular arithmetic did not produce an effect on overall performance.

Question 1: *Do you know modular arithmetic?*	
Multiple Choice Options:	*A. Yes, I use it every day.*
	B. Yes, but I don't really ever use it.

	C. I learned about it.
	D. I don't know what that is.
	E. Other [Free Response Field]

Table 10. Post-Session Survey, Modular Arithmetic Question Prompt.

Multiple Choice Options	Response %
A. Yes, I use it every day.	10%
B. Yes, but I don't really ever use it.	15%
C. I learned about it.	21%
D. I don't know what that is.	53%
E. Other [Free Response Field]	1%

Table 11. Post-Session Survey, Modular arithmetic Response Proportion.

Chance Questions. These questions measure several tenants of Prospect theory (Kahneman & Tversky, 1979b; Tversky & Kahneman, 1981b; 1992 and Tversky & Shafir 1992). According to the authors, Question 1 and 2 measure the *certainty effect* with non-monetary outcomes. In decision-making under the certainty effect, people tended to choose the item that appeared to be more certain (e.g., Choice B. "Guaranteed"). This preference is interesting because the expected value of Q1, Choice A is a 1 ½ week vacation compared to Choice B that offers only 1 week. The expected utility of each choice in Question 2 presents a similar probability. Question 3 and 4 measure the *failure of the substitution axiom* which is related to risk or chance. Specifically, Question 3 presents the *probability* of winning where Question 4 presents only the *possibility* with very low probability of winning. In Question 3, it is most interesting that even though the expected value of winning between choice A or B in questions 3 and 4 are identical (e.g., $6,000 x 45% = $2,700 and $3,000 x 90% = $2,700). However, the authors reported in Question 3, the preferred choice B is made on the larger percentage chance 90%, while the preference in Question 4 switches to Choice A, the higher dollar amount ($6,000).

Modification. In our study, questions in this section of the post-session survey were modified (Table 12) from versions of the original problems (Table 13) presented by Kahneman and Tversky (1979). These problems present options with positive outcomes (for more on options with negative outcomes, see Kahneman & Tversky, 1979b; Markowitz, 1952; Williams, 1966). In questions one and two, we modified the questions to be more inclusive of preferred destinations beyond Western and Central Europe. In questions three and four, keeping the original intent, and for our purposes in an unproctored experiment, we clarified the problems by replacing the decimals with percentages (for more information on difficulty quantifying decimals, fractions, and percentages, see Jacobs Danan & Gelman, 2018; Vamvakoussi & Vosniadou, 2010)

Results. We found that the participants in Experiment 1 performed similarly to those in the Kahneman and Tversky study on Q's 1 and 3 but choose B in Q2 (see Table 14 for results, and Table 15 for response comparisons with the original study), (see Appendix M for comparison by condition). On Q4, all group preferences agreed with the previous study, except for those participants in the Early-Certain condition, who preferred choice B.

Our participants demonstrated less preference reversal than those in the original study. However, the foundational theory presented by the authors of Prospect theory holds. People make choices that are (1) perceived to be more certain, (2) perceived to have a greater value, (3) and have difficulty comparing probabilities.

Question	Choice A	Choice B
Q1	50% chance of winning a 3 week, all expenses paid vacation to 3 locations of your choice	Guaranteed 1 week, all expenses paid vacation to 1 location of your choice
Q2	5% chance to win a 3 week, all expenses paid vacation to 3 locations of your choice	10% chance to win a 1 week, all expenses paid vacation to 1 location of your choice
Q3	45% chance to win $6,000	90% chance to win $3,000
Q4	1% chance to win $6,000	2% chance to win $3,000

Table 12. Modifications of the original choice problems presented by Kahneman and Tversky, 1979.

Question	Choice A	Choice B
Q1	50 % chance to win a three-week tour of England, France, and Italy	A one-week tour of England, with certainty
Q2	5% chance to win a three-week tour of England, France, and Italy*	10% chance to win a one-week tour of England
Q3	(6,000, .45)	(3,000, .90)
Q4	(6,000, .001)	(3,000, .002)

Table 13. Original choice problems presented by Kahneman and Tversky (1979).

Question	Response	%
Q1	A	23%
	B	77%
Q2	A	34%
	B	66%
Q3	A	12%
	B	88%
Q4	A	53%
	B	47%

Table 14. Chance questions – Response, all conditions

Source/Condition	Question 1 Preferred Choice	Question 2 Preferred Choice	Question 3 Preferred Choice	Question 4 Preferred Choice

Kahneman & Tversky	B	A	B	A
Early-Uncertain	B	B	B	A
Early-Certain	B	B	B	B
Late-Uncertain	B	B	B	A
Late-Certain	B	B	B	A

Table 15. Comparison of responses, Kahneman and Tversky (1979) and the four experiment conditions. Participants showed less preference reversal than those in the previous study.

Intolerance to Uncertainty Scale. To analyze these data, the response frequency and Likert value for each question was summed to provide an overall 12-question mean score (see Table 16).

Condition	12 Question Mean
EU	M = 34.07
EC	M = 33.04
LU	M = 34.28
LC	M = 33.89

Table 16. Intolerance to Uncertainty Scale. Experiment 1, mean score over 12 Likert-style prompts.

When comparing groups, a higher score would suggest that participants who had a lower tolerance for uncertainty, might be more inclined to stay on the starting portal if they perceived switching to be too risky, regardless of the condition. We did not find a significant difference between groups, $F(3, 47) = .64$, $p = .60$. While no pre-test was given to determine participants' intolerance to uncertainty prior to competing the experiment, we take these results to suggest that following the performance phase, all groups reported similar responses indicative of no influence of the factors related to an intolerance to uncertainty.

We analyzed how our subject pool compared to normative samples. However, the IUS-12 scale is typically used in clinical settings to evaluate and diagnose anxiety disorders (see Figure for sample of questions, Appendix xx for complete scale). Beyond research on scale validity, to our knowledge, instructional scoring guidelines are unavailable. We were able to find a simple graph with which to make a general comparison.

Carleton et al., (2012) provided a kernel density estimation of IUS-12 scores across groups (see Figure xx.) that we used to compare the mean scores from our four experimental conditions in each experiment. The general population samples comprised university undergraduates and community members. The remaining five groups were participants identified with anxiety disorders related to uncertainty.

The mean scores in our sample fall within the panic disorder curve in Carleton's figure. To make sense of this result, we consider the current world events and that these data were collected during the COVID-19 pandemic. Recent research demonstrates COVID-19 has produced societal and economic uncertainty, thus increasing anxiety in every-day responsibilities for survival. Mturkers are "on-demand workers [and] are only paid for time they spend working" (Condon & Wichowsky, 2022). During the past few years anxiety levels in the United States have increased 3-fold (Santabárbara et al., 2021). We suggest the high IUS-12 scores are situational related, rather than inherent qualities of Mturk workers.

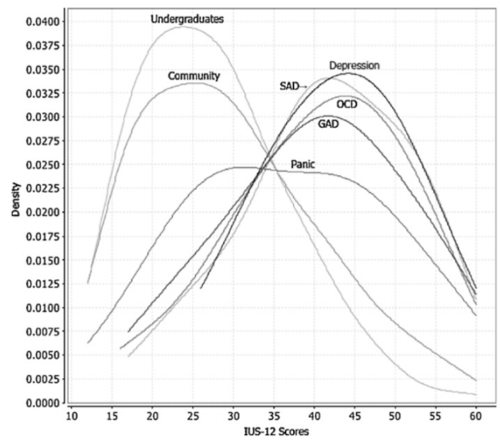

Figure 14. Kernal density estimation of IUS-12 scores across groups, with density reflecting frequency of cases along IUS-12 scores. Panic = panic disorder, SAD = social anxiety disorder, GAD = generalized anxiety disorder, OCD = obsessive compulsive disorder, depression = major depressive disorder (Carleton et al., 2012).

Experiment 1 Discussion

In our first experiment, we were interested in the influence of uncertainty and projection completion on the Sunk Cost Fallacy. In the crosstabulation, we found that more participants always chose to stay on the starting portal than those who always chose to switch. We believe this demonstrates that the Sunk Cost Fallacy exists and can be measured in a task-oriented experiment. Although inconsistent between trials, we also found support that separately, uncertainty and projection completion are an operational strategy to produce the effects of the fallacy. In addition, we also found some cooperative (magnification) effects. Results from surveys provided details about our participant pool in support of and extending the foundational theory into an experimental paradigm to measure progress decisions. The Inter-trial Questionnaire revealed switching portals to complete the HIT faster was a major motivation of M-turk workers. The Post-Session, Task-Related questions revealed five themes in portal switching behavior. Participants skilled in using modular arithmetic would make solving the cyphers easier, but since most did not report proficiency, we can assume that a command of the math technique did not produce an effect on overall performance. From the results of the Chance questionnaire, we learned that although responses slightly differed from the original study, overall, our participants had difficulty mentally comparing probabilities. In fact, this limitation might extend to the difficulty solving cyphers and efficiently comparing the portal comparisons. Finally, results from the Intolerance to Uncertainty Scale, we found no significant difference between conditions but that all groups demonstrated a heightened level of intolerance to uncertainty. Experiment 2 continued our research into the effects of uncertainty on the Sunk Cost Fallacy and brought in our third variable of interest, mental effort.

Experiment 2: Research Design

In experiment 2, we investigated the effects of uncertainty and task difficulty (i.e., mental effort). Experiment 2 followed the same procedure and recruitment in Experiment 1 as described, with a change in manipulated variables. Instead of an Early and Late presentation of the switch message, participants all received the Late portal switch message interval (in the 3rd cypher, following the correct entry of the 1st character) and were randomly assigned into a Simple or Hard condition, representing the amount of mental effort needed to solve the encrypted passphrases. This variable was implemented as two levels of difficulty in passphrase complexity. The Simple condition contained 4 matched pairs (in which a pattern is repeated which we theorize makes the task easier to perform), whereas the Hard condition contained none.

Matched Pair Creation and Rationale. To create randomized pass phrases, an online random string generator was used (Randomness and Integrity Services Ltd., 2019). Duplicate and adjacent letters were allowed. Phrases were ranked in order of difficultly (0 = most difficult, 4 = easiest) based on the phrase length (e.g., character count [3,15]) and the number of matched alpha-numeric pairs. A matched pair occurred if the letter, assigned to the same key integer, appeared twice in the passphrase. In Table 17, for example, the letter 'P' and the integer '7' are a matched pair. There are 4 matched pairs in this example, denoted by red, blue, green and yellow font (see Appendix G for complete passphrase and key development).

We theorized that matched pairs should be more quickly recognized from a deciphered string character, making the alpha-numeric table less necessary. For example, once the repeated pattern is recognized, it can be used to decipher the password more quickly without needing to refer to the table. This might reduce mental effort and time to solve the phrase, as well as possibly reducing the in-game currency wasted on incorrect entries. The solutions for the encrypted passphrases were produced with an Excel formula and python code.

	Zero Matched Pairs	Four Matched Pairs
Encrypted Passphrase	Y C V L I H D S W V U N H E S	W D **P X A** G **K** R Y **K A** R **X** M **P**
Key (repeated) [427]	4 2 7 4 2 7 4 2 7 4 2 7 4 2 7	4 2 **7 4 2** 7 **4** 2 7 **4 2** 7 **4** 2 **7**

Table 17. Example of zero and four matched pairs, encrypted passphrase, and key.

Participants. In Experiment 2, 387 participants were quasi-randomly assigned to one of four conditions based upon the certain or uncertain manipulation and the task difficulty (mental effort) in a Simple or Hard condition. The four conditions were: Simple-Certain (control), Simple-Uncertain, Hard-Certain, and Hard-Uncertain.

Experiment 2: Research Questions and Hypotheses

Research Question 1. Does uncertainty effect the sunk cost fallacy?

Hypothesis 1. The sunk cost fallacy occurs more in uncertain conditions. As in Experiment 1, we expect uncertainty plays a role in the decision to persist or withdraw from a task. Those in the uncertain condition will switch less from an initially chosen project (signaling the sunk cost fallacy) than those in the certain condition.

Research Question 3. Does project difficulty effect the sunk cost fallacy?

Hypothesis 3. The sunk cost fallacy occurs more in difficult projects. New to Experiment 2, we predict that task difficulty contributes to the decision to persist or withdraw from the task. Those in the Hard conditions, which requires more mental effort, will switch less than those in the Simple conditions. Difficulty is manipulated by presenting encrypted passphrases with matched pairs. As described above, it was theorized that more matched pairs required less mental effort and resources, and possibly result in less entry errors. Participants were quasi-randomly assigned to one of two difficulty conditions. The dependent variable, portal switch, was binomial (yes/no).

Research Question 5. Does the combination of uncertainty and project difficulty effect the sunk cost fallacy?

Hypothesis 5. The sunk cost fallacy occurs more in uncertain conditions when the project is more difficult. Task difficulty and uncertainty were predicted to cooperative or magnify their effects in to the decision to persist or withdraw from the task. Those in the Hard-Uncertain condition will switch less and spend more resources than those in the Hard-Certain, or Simple conditions.

Experiment 2: Data Collection

Data collection for Experiment 2 ran from August 7, 2021, through August 24, 2021, on Amazon MTurk. All other parameters for data preparation were identical to Cypher 1.

Experiment 2: Data Preparation

A total of 9 HITs were posted, N = 850, which, after the data was prepared, n = 387 (Table 17). Participants by gender: Male, N = 228, Females N = 156, Other, N = 5, Age, *M* = 38.56, SD 11.08, Min = 20, Max 75. See Table 18.

Experiment 2: Data Preparation and final n						
Experiment	Condition	HIT Request n	Rejected (M-turk) n	Post M-turk Removal n	Retained n	**Combined HIT n**
Cypher 2	Simple-Certain	100	30	20	50	**97**
		100	44	9	47	
	Hard-Certain	100	33	4	53	**97**
		100	26	33	44	
	Simple-Uncertain (control)	100	33	28	39	**103**
		100	42	18	40	
		50	12	14	24	
	Hard-Uncertain	100	41	15	44	**90**
		100	35	19	46	
	Total	850	296	430		**387**

Table 18. Experiment 2 Data Preparation and final n.

Experiment 2: Analyses

To evaluate the influence of uncertainty, project completion on portal switch behavior, chi-square tests of independence were performed to examine the relationship between the independent variables, with rates of switching to a new portal (a binomial, dependent variable) in each trial. As in Experiment 1, a preliminary, exploratory analysis was performed to further investigate resource utilization of time (MANOVA, Bonferroni correction) and coins (Kruskal-Wallis H test, Benjamini Hochberg correction), (see Appendix J).

Crosstabulation. A crosstabulation for Experiment 2 demonstrates that overall, irrespective of condition, 172 participants *always chose to stay* on the starting portal compared to 105 who *always switched* (see Table 19). Participants who chose to change their strategy (e.g., stay in trial 1, switch in trial 2) were nearly equal. These results demonstrate that the effects of the Sunk Cost Fallacy can be measured within a progress decision, task-oriented experiment.

A paired samples t-test was conducted between those who stayed or switched in both trials. There was a significant difference between those who always stayed (M = 15.64, SD = 1.57) and those who always switched (M = 9.55, SD = 2.16), t(10) = 6.30, p < .001; switch → stay (M = 4.45, SD = 1.97) compared to stay → switch (M = 5.64, SD = 2.06), t(10) = 3.99, p = .001; always stayed (M = 15.64, SD = 1.57) compared to stay → switch (M = 10.09, SD = 2.70), t(10) = 5.05, p < .001. There was no significant difference between those who always switched (M = 9.55, SD = 2.16) compared to stay → switch (M = 10.09, SD = 2.70), t(10) = .54, p = .30.

Experiment 2: Trial 1 Switch * Trial 2 Switch Crosstabulation							
		Trial 2 Switch				Total	
		Stay		Switch			
		n	%	n	%	n	%
Trial 1 Switch	Stay	172	77.7%	62	37.1%	233	60.2%
	Switch	49	22.3%	105	62.9%	154	39.8%
Total		220	100.0%	167	100.0%	387	100.0%

Table 19. Crosstabulation, Experiment 2. Number of participants who chose to always stay vs. always switch, and those who changed strategy between trials.

Experiment 2: Trial 1 Results

To evaluate the main effects of uncertainty (H1) on portal switch behavior in Trial 1, chi-square tests of independence were performed to examine the relationships between the independent variables with rate of switching to a new portal. However, no significant differences between the Uncertain and Certain conditions were found, χ^2 (1, N = 387) = 0.79, p = .37. Similarly, no significant differences between the Simple and Hard conditions were found χ^2 (1, N = 387) = 1.65, p = .65, and neither were cooperative/magnification effects (no significant differences between the Simple-Uncertain, Simple-Certain, Hard-Uncertain, and Hard-Certain conditions were found), χ^2 (3, N = 387) = .74, p = .39.

Experiment 2: Trial 2 Results

Again, to evaluate the main effects of uncertainty (H1) on portal switch behavior in Trial 2, chi-square tests of independence were performed to examine the relationships between the independent variables with rate of switching to a new portal. No significant differences between the Uncertain and Certain conditions were found χ^2 (1, N = 387) = 1.81, p = .58, and once again neither were there significant effects of difficulty, χ^2 (1, N = 387) = 1.99, p = .28 or any cooperative/magnification effects χ^2 (3, N = 387) = 0.13, p = .72.

Experiment 2: Survey Results

As in Experiment 1, the same surveys and questionnaires were presented to measure various aspects of participants' decision-making process.

Inter-Trial Survey. The results from the multiple-choice questions (“*Did you enjoy this task?”, “How difficult would you say this task is?”,* “*Why did you stay/switch portals?”*) were aggregated, and response proportions are provided in Table 20.

In summary, most participants reported enjoying the experiment, found that solving the cyphers was moderately easy, and switched because they believed it would be faster. Switching portals because it was perceived as faster aligns with the Mturk subject pool (M-turkers are motivated to complete tasks quickly to ensure they are making money and being effective); and may provide insight into why we did not find more significant results in Cypher 2 between the Simple and Hard conditions. It appears that regardless of the difficulty and effort required to solve the cyphers, participants were more mindful of the resource of time. That is, regardless of whether the cypher required more mental effort or not, participants tended toward a strategy that was perceived to be faster.

Did enjoy?	%	How difficult?	%	Why switch?	%
no	5%	easy	24%	faster	64%
yes	84%	moderately easy	55%	easier	30%
indifferent	10%	moderately hard	19%	bored	0%
don't know	0%	hard	1%	don't know	1%
other	0%	other	0%	other	4%

Table 20. Experiment 2. Inter-Trial Survey.

Post Session Survey Questions.

Prompt Question. *Do you know modular arithmetic?*

Most participants in Experiment 2 also did not have a working knowledge of modular arithmetic (73 %) (see Tables 21, 22 below, Appendix L for proportions split by condition). Participants skilled in this math technique would make solving the cyphers easier, although knowing it was not necessary to complete the tasks. This metric provides information about switching behavior. For example, if a large group of participants knew and often used modular arithmetic, this could explain resource usage, particularly the time spent from the start of the trial until the switch opportunity, and overall time to complete the trial. Using modular arithmetic would allow participants to use a formula to quickly solve the cypher, saving time and possibly coins spent on errors made. Otherwise, participants followed the experiment instructions to compare a character in the passphrase to the alphanumeric table, then using the integer keys to count backward to find the deciphered character. Since most did not report proficiency, we can assume that a command of modular arithmetic did not produce an effect on overall performance.

Question 1: *Do you know modular arithmetic?*	
Multiple Choice Options:	*A. Yes, I use it every day.*
	B. Yes, but I don't really ever use it.
	C. I learned about it.
	D. I don't know what that is.
	E. Other [Free Response Field]

Table 21. Experiment 2. Prompt Question

Multiple Choice Options	Response %
A. Yes, I use it every day.	14%
B. Yes, but I don't really ever use it.	12%
C. I learned about it.	22%
D. I don't know what that is.	51%
E. Other [Free Response Field]	0%

Table 22. Experiment 2. Post-Session Survey, Modular arithmetic Response Proportion by Question.

Chance Questions. This questionnaire was identical to the modified version that appeared Experiment 1.

Results. We found that the participants in Experiment 2 performed similarly to Experiment 1, and to those in the Kahneman and Tversky study on Q's 1 and 3 but choose B in Q2 (see Table 23 for modifications, Table 24 for results, and Table 245for comparisons between the original study and the modified version). On Q4, all group preferences agreed with the previous study, except for those participants in the Simple-Certain condition, who preferred choice B (Table 24).

Our participants demonstrated less preference reversal than those in the original study. However, the foundational theory presented by the authors of Prospect theory holds. People make choices that are (1) perceived to be more certain, (2) perceived to have a greater value, (3) and have difficulty mentally processing fractions and percentages.

Question	Choice A	Choice B
Q1	50% chance of winning a 3 week, all expenses paid vacation to 3 locations of your choice	Guaranteed 1 week, all expenses paid vacation to 1 location of your choice
Q2	5% chance to win a 3 week, all expenses paid vacation to 3 locations of your choice	10% chance to win a 1 week, all expenses paid vacation to 1 location of your choice
Q3	45% chance to win $6,000	90% chance to win $3,000
Q4	1% chance to win $6,000	2% chance to win $3,000

Table 23. Modifications of the original choice problems presented by Kahneman and Tversky, 1979.

Question	Response	%
Q1	A	24%

	B	76%
Q2	A	31%
	B	69%
Q3	A	11%
	B	89%
Q4	A	53%
	B	47%

Table 24. Chance questions – Experiment 2. Response proportions, all conditions.

Source/Condition	Question 1 Preferred Choice	Question 2 Preferred Choice	Question 3 Preferred Choice	Question 4 Preferred Choice
Kahneman & Tversky	B	A	B	A
Simple-Uncertain	B	B	B	A
Simple-Certain	B	B	B	B
Hard-Uncertain	B	B	B	A
Hard-Certain	B	B	B	A

Table 25. Comparison of responses - Experiment 2. Kahneman and Tversky (1979) and the four experiment conditions. Participants showed less preference reversal than those in the previous study.

Intolerance to Uncertainty Scale. Results are similar to those presented in Experiment 1. There was no significant difference between the conditions, $F(3, 47) = 1.09$, $p = .37$, and the mean scores, according to Carleton, et al., (2012), fall within the range for panic disorder (Table 26).

Condition	Total Score	12 Question Mean
SU	3627	$M = 35.21$
SC	3393	$M = 34.98$
HU	3353	$M = 37.26$
HC	3528	$M = 36.37$

Table 26. Intolerance to Uncertainty Scale. Experiment 2 results, mean score over 12 Likert-style prompts.

Task Related Questions**.** In Experiment 2, we again see five themes emerge (1) those who were influenced by the sunk cost fallacy (*"I was in the middle of deciphering every time it asked to switch, so I didn't want my effort to go to waste."*), (2) those who understood the comparison between the two portals, either performing quick mental math (*"I think I had 4 left at 9 each, or by switching it was 7 left at 5 each. I went with 35 instead of 36, in hopes of finishing quicker."),* or accepted the switch message prompt that stated the alternate portal contained shorter cyphers (*"I went with my trusted colleague's suggestion."),* (3) those who seemed to choose based upon perceived performance (*"I didn't do the math and didn't think it would really be any faster.")*, (4) storyline influence ("*to catch the criminal*"), or (5) personal motivation (*"I just wanted to see what would happen."*) (See Tables 27 – 29).

Participants who reported they stayed on the starting portal.

1. *If you ever chose to* **stay** *on the current server when given the choice to switch, how/why did you make that decision? List any details or thoughts you had in order.*

Example Response 1	*"Better what I know tha[n] something new I'm not sure... This made me stay."*
Example Response 2	*"Since was doing well on the one I was on I felt that switching gave some risk"*
Example Response 3	*"I stayed because I wanted to finish what I started. It's as simple as that."*
Example Response 4	

	"I had already solved one or 2 cyphers so staying seemed like it would be the better option."
Example Response 5	*"I didn't do the math and didn't think it would really be any faster."*
Example Response 6	*"I was in the middle of deciphering every time it asked to switch, so I didn't want my effort to go to waste."*

Table 27. Experiment 2, Participants who stayed on the starting portal.

Participants who reported they switched from the starting to the alternate portal.

2. *If you ever chose to* ***switch*** *to the other server during this experiment, how/why did you make that decision? List any details or thoughts you had in order.*

Example Response 1	*"I calculated the number of characters that would be required both ways and it was clear that switching would mean less work."*
Example Response 2	*"I think I had 4 left at 9 each, or by switching it was 7 left at 5 each. I went with 35 instead of 36, in hopes of finishing quicker."*
Example Response 3	*"I just wanted to see what would happen."*
Example Response 4	*"I realized it was actually faster to cut the number of letter i had to complete in half."*
Example Response 5	*"I went with my trusted colleagues suggestion."*
Example Response 6	*"…it said the others I would be doing would only be 5, so I thought that would be faster."*

Table 28. Experiment 2, Participants who switched from the starting to the alternative.

In response to the two questions above, participants also reported if they changed switching strategy between trial 1 and 2.

Example Response 1	*"The second time I was offered a switch, I had already completed three cyphers, and didn't want to start over."*
Example Response 2	*"…to catch the criminal."*
Example Response 3	*"At second time I chose the option to switch to know what is in it."*
Example Response 4	*"The first time I switched because I thought it would be easier. The second time I stayed to finish the game."*
Example Response 5	*"If the first server is difficult, I will chose to other server."*
Example Response 6	*"I did the opposite on the second part as I did on the first. I didn't have any reason for either. I just didn't want to do the same thing."*

Table 29. Experiment 2, Participants who changed decision between trial 1 and 2.

Experiment 2 Discussion.

In our second experiment, we continued the investigation into the influence of uncertainty and the possibility of a cooperative/magnifying effect of mental effort on portal switch behavior. Results from the crosstabulation again showed that more participants always chose to stay on the starting portal than those who always chose to switch and confirms the existence of the Sunk Cost Fallacy that can be measured in a task-oriented experiment. Unfortunately, we did not find an influence of uncertainty or task difficulty in measuring mental effort on portal switching behavior in either trial.

Results were like those found in Experiment 1 in that participants were motivated to complete the tasks quickly to ensure they efficiently used their time to earn money, were not proficient in modular arithmetic, and preferred choices perceived to be more certain and with a greater value and had difficulty comparing probabilities. Intolerance to Uncertainty scores indicated that all conditions responded in a manner consistent with panic disorder. Finally, we again found five emergent themes in portal switching behavior in the Task Related, free response survey; (1) those who were influenced by the Sunk Cost Fallacy, (2) those who understood the comparison between the two portals and switched, and (3) those who chose based upon other factors such as perceived personal performance, storyline influence, and motivation.

CHAPTER 4

EXPLORATORY ANALYSES

As part of the overall effort to explore and understand sunk cost fallacy, another undertaking was examining whether there could have been an effect of participant strategy operating across both experiments, and in particular between each trial. For example, several participants reported they switched or stayed in the first trial but made the opposite choice in trial 2. After reviewing the open-ended survey questions from the survey, we found examples where decisions were made that appear to be unrelated to the effects of the sunk cost fallacy. For example, a participant stated, "*I just switched on the second round out of curiosity. On the first one I stayed on the same one because it was working well for me.*" Another reported, "*Thought it was a bait the first time around and decided to give it a shot the second.*"

Change in Strategy Between Trials

To understand if participants might have randomly changed strategy between trials, we conducted an exploratory analysis. A McNemar's chi-square was used for ***within*** subjects comparisons (Pembury Smith & Ruxton, 2020). The McNemar tests for consistency in responses across two treatments. In other words, this test demonstrates whether the difference in responses between trial 1 and 2 are random or not. Random responses would be an indication of a change in task strategy between trial 1 and trial 2.

Each condition, across trials, and in both experiments was analyzed independently. Only in the Late-Uncertain condition did participants differ significantly between trial 1 and trial 2, $\chi^2(1, N = 98) = 5.12$, $p = .02$, which suggests that in

Experiment 1, participants in this condition in changed task strategy between trial 1 and trial 2.

Exploratory Analyses: Resource Utilization

We realize that studying the Sunk Cost Fallacy in an abstract, game-like scenario removes much of the ecological reality necessary to understand the strength of the effects in an applied setting. In real life, resources are freely spent toward accomplishing some goal, while resources are a required to complete work, completely withdrawing from a project could also be an alternative, ceasing spending altogether. In Cypher, to receive compensation for work performed, participants are forced to spend resources to complete the HIT.

Exploratory Analyses for each trial, across both experiments, were conducted with a MANOVA with Bonferroni corrections on time spent and a Kruskal-Wallis H test and Benjamini Hochberg corrections on coins spent to specifically test resource utilization by condition and between participants who stayed or switched to the alternate portal (see Appendix J).

The exploratory analyses provided valuable insights into the efficacy of the experimental manipulations, as well as bringing to light possibilities for the current motivation of Mturk workers.

The uncertain manipulation had an effect to delay forward progress (i.e., application in cyber defense). Comparing the Late-Certain and Late Uncertain conditions who both switched or did not – those in the Uncertain conditions spent significantly more time than those in the Certain conditions (see Table 30). This result might suggest that the uncertain manipulation had some affect in delaying forward progress to complete the trial, regardless of whether a participant chose to switch portals or not. Although this finding is not in line with the traditional theory, it does suggest that the manipulation delayed forward progress.

Time to Complete Trial						
Condition	**N**	**Mean (s)**	**</>**	**Condition**	**N**	**Mean (s)**
Simple-Certain, did NOT switch	53	354.02	<	Hard-Certain, did NOT switch	47	441.06
				Hard-Uncertain, did NOT switch	46	456.00
Simple-Uncertain, did NOT switch	60	356.93	<	Hard-Certain, did NOT switch	47	441.06
				Hard-Uncertain, did NOT switch	46	456.00

Table 30. Comparison of Simple and Hard conditions who did not switch.

CHAPTER 5

GENERAL DISCUSSION

The combined crosstabulation for Experiment 1 and 2 demonstrates that overall, irrespective of condition, out of a combined total of 775 participants, 331 participants *always chose to stay* on the starting portal compared to 223 who *always switched* (see Table 31.). Participants who chose to change their strategy (e.g., stay in trial 1, switch in trial 2) were 221.

Although we did not find support that our manipulations created a consistent effect in the experiments, more people stayed in the starting portal. The Sunk Cost Fallacy is an existing bias that occurs beyond single-decision scenarios, and can be measured within a progress decision, task-oriented experiment. Our results indicate that eliciting decision-making biases, specifically the SCF, can "make the overall attack economics unfavorable" (Steingartner et al., 2021, p. 4). In a cyber defensive scenario, employed as a deceptive strategy, SCF could cause an adversary to make mistakes and waste resources, effectively delaying and thereby deterring enemy cyber attackers.

Experiment 1 and 2: Trial 1 Switch * Trial 2 Switch Crosstabulation

		Trial 2					
		Stay		Switch		Total	
		N	%	N	%	N	%
Trial 1	Stay	331	77.7%	122	37.1%	452	60.2%
	Switch	100	22.3%	223	62.9%	323	39.8%
Total		431	100.0%	345	100.0%	775	100.0%

Table 31. Combined Crosstabulation for Experiments 1 and 2.

Hypothesis 1: Certainty

The sunk cost fallacy occurs more in uncertain conditions.

Certainty was tested in both experiments. In Experiment 1, trial 2 we found support for H1 as the Uncertain switch message elicited the sunk cost fallacy more than the Certain message. No support was found in experiment 2 (see Table 31).

HYPOTHESIS	HYPOTHESIS SUPPORTED?	TESTING EXPERIMENT	RESULT TRIAL	RESULT DETAIL
H1: Certainty	No	1	1	No significant difference
	Yes	1	2	Uncertain > Certain
	No	2	1, 2	No significant difference

Table 31. Hypothesis 1, results.

We realize that studying the Sunk Cost Fallacy in an abstract, game-like scenario removes much of the ecological reality necessary to understand the strength of the effects in an applied setting. In real life, resources are freely spent toward accomplishing some goal. Additionally, while resources are a required to complete work, completely withdrawing from a project is also an alternative and one that was not available to participants in this experiment.

Results from the Chance Questionnaire showed that participants preferred options that appeared to be more certain, and of higher value. However, these preferences were not represented in the cypher task behaviors; perhaps making a rapid decision between two simple choices is not equivalent to making a similar decision amid a task that requires more mental effort. This will require more exploration in future studies.

Statements from the survey also suggested that participants did not read or understand the comparison between the portal as presented in the switch prompt (*"I didn't do the math and didn't think it would really be any faster."; "I chose to stay on the current server . . . it seemed like the other choice would take more time.* If it had, maybe participants may have chosen to switch more often. That is, perhaps using the switch prompt contributed to mental effort and uncertainty. The literature does show disagreement regarding the effects of uncertainty, project completion level and the types of resource investment that underly the effects of the sunk cost fallacy on decision-making. The inconsistency in the results mirror those found in the literature.

Hypotheses 2: Project Completion

The sunk cost fallacy occurs more when a project is closer to completion.

The effects of project completion were tested in Experiment 1. In trial 1, we found support but not in trial 2 (see Table 32).

HYPOTHESIS	HYPOTHESIS SUPPORTED?	TESTING EXPERIMENT	RESULT TRIAL	RESULT DETAIL
H2: Project Completion	No	1	1	No significant difference
	Yes	1	2	Late > Early

Table 32. Hypothesis 2.

We speculate that the difference between the early and late presentation of the portal switch message, intended to manipulate project completion, was not severe or perceptibly different enough to create a strong or consistent effect.

Hypothesis 3: Project Difficulty

The sunk cost fallacy occurs more in difficult projects.

Difficulty (task) was tested in experiment 2. We did not find support for H3 in either trial (see Table 33).

HYPOTHESIS	HYPOTHESIS SUPPORTED?	TESTING EXPERIMENT	RESULT TRIAL	RESULT DETAIL
H3: Task Difficulty (mental effort)	No	2	1, 2	No significant difference

Table 33. Hypothesis 3.

This finding contradicts the findings of Cunha and Caldieraro (2010, 2011) who said that mental effort is highly valued, and thus strongly influences the Sunk Cost Fallacy. Participants in the Hard condition *should* have stayed more often because of the higher effort investment; however, most participants who switched reported doing so because they believed it would be faster. We speculate the resource of time spent in the experiment itself had a higher investment value for these participants than the mental effort of solving the cyphers. These effects would have been working to counteract the effects of the SCF when they realized their time sunk into the starting portal would not contribute to the desired outcome - finishing as fast as possible.

Hypothesis 4: Certainty + Project Completion

The sunk cost fallacy occurs more in uncertain conditions when a project is closer to completion.

The cooperative effects of certainty and project completion were tested in experiment 1. In both trials, we found an interesting effect in that the Early-Uncertain condition switched less than those in the Late-Certain condition (see Table 34). No other comparison was significantly different. As we observed occasional effects of both uncertainty and project completion (e.g., Tables 30 and 31 above) the result here is opposite of our expectation that a Late-Uncertain condition would actually show the strongest SCF result.

HYPOTHESIS	HYPOTHESIS SUPPORTED?	TESTING EXPERIMENT	RESULT TRIAL	RESULT DETAIL
H4: Cooperative Effects	Contradicted	1	1, 2	Early-Uncertain < Late-Certain

Table 34. Hypothesis 4, results.

Hypothesis 5: Certainty + Project Difficulty

The sunk cost fallacy occurs more in uncertain conditions when a project is more difficult.

The cooperative effects of certainty and task difficulty were tested in experiment 2. No support for H5 was found in support for H5 in either trial (see Table 34). Instead of cooperating/magnifying, we speculate the certainty and difficulty manipulations washed out any effects.

HYPOTHESIS	HYPOTHESIS SUPPORTED?	TESTING EXPERIMENT	RESULT TRIAL	RESULT DETAIL
H5: Cooperative Effects	No	2	1, 2	No significant difference

Table 35. Hypothesis 5, results.

Lessons Learned - Limitations

Developing a new experimental platform to test the complexity of decision-making biases is difficult. Overall, we found little significant differences between conditions across the two CYPHER experiments. This might be due to factors of the experimental design, individual differences in participants' strategy to complete tasks, and our participant pool from Amazon MTurk.

Factors of Experimental Design. First, we believe some participants may not have fully read or understood the uncertain and certain switch messages. Survey responses point to different motivations when deciding to stay or switch. For example, when asked why the decision to stay or switch was made, some participants stated that based their choices on if they felt they were doing well on the current portal and switched if they became bored or when the task seemed too difficult. Furthermore, while we intended the storyline element to create interest and motivation, and participant feedback suggested the overall experience was enjoyable, we believe some participants switch decisions might have been motivated by the game storyline (to catch the thief) rather than the task instructions.

It is also possible that the presentation of large bodies of text and the expectation that participants would take the time to read and comprehend the communication might be an unfeasible requirement in an online research platform like Amazon Mturk. For example, after reading the switch message prompt:

"A **trusted colleague** discovered a new trail left by CYPHER that **looks like** a shortcut to reaching your target's whereabouts. She offers you passage through a portal with codes that **she says** are **(5)** characters long. You can switch to the new portal and solve **(7)** cyphers to complete your mission. Do you want to switch portals?"

A participant reported their reason for switching portals was they would "only have to crack the rest of the 5 instead of 7." It appears the participant in the Early-Uncertain condition read the message but misunderstood what it said. Like the starting portal, the alternate also contained 7 cyphers, but the *length* was only 5 characters long, compared to the possible 5 – 11 lengths in the starting portal. So, while the participant made the best choice to switch, the format and presentation of the information or the carelessness of participants reading it may have influenced decision-making and reduced any effect of the uncertain manipulation. Future research should reconfigure the narrative to investigate and compare the influence of narrative variations (e.g., simplify, removing the storyline completely).

Second, we believe the difference in the time interval of the switch message presentation between Early and Late was not severe enough. To review, in the Early condition, the switch message was presented in the 2^{nd} cypher, following the correct entry of the 2^{nd} character. In the Late condition, the switch message was presented in the 3^{rd} cypher, following the correct entry of the 1^{st} character. In other words, the timing of late presentation of the portal switch message was not perceptibly different enough from the early presentation and thus, not representative of a good comparison. In future experiments, the timing of the Late interval will be re-calculated to increase the real and perceptual difference from the Early.

Third, while the difficulty manipulation (Simple versus Hard cyphers) resulted in a significant difference in resource utilization per the intended game design (see Exploratory Analyses, Appendix J), it did not significantly influence portal switching. That is, our hypothesis that participants in the Hard condition would by influenced by the Sunk Cost Fallacy and switch less than those in the Simple condition was not supported. From the survey responses, we believe participants switched to lessen the mental effort and time required to solve the more difficult cyphers. Thus, rather than being influenced by the sunk cost fallacy, participants appear to have favored switching portals to reduce mental effort because while the cyphers in the Hard condition were still more difficult, they were shorter. We believe a better future strategy is to reduce the overall complexity and related effort required to solve cyphers and increase the number of trials to reduce the novelty and difficulty of the task. We theorize that this approach will reduce effort avoidance and clarify the portal switch opportunity as participants learn the task.

Participant Pool. Amazon Mturk workers perform well in tasks that can be completed quickly. Most do not take the time to read long passages of texts. It is possible in our experiments, that even with the colorful narrative designed to engage and personally motivate participants, our Mturk workers simply wanted to complete the HIT as quickly as possible and with minimal effort.

Although we restricted participants living outside of the United States, we suspect that some workers were able to circumvent this through technology (e.g., using a VPN). The reason for our suspicion is that many responses to open ended questions were grossly misspelled and demonstrated little comprehension of the questions.

We began data collection while requiring the "Masters" Certification, which is awarded to Mturk workers by Amazon via a threshold of performance over multiple HITs. The data collected was clean, participants followed instructions and completed the task as required. However, the rate at which we could collect was very slow. A few months into our collection, we learned that these certifications no longer were being awarded and therefore the subject pool was smaller than we needed. We made the decision to remove the requirement and do the necessary data cleaning on the back end with a more variable sample While this exponentially increased our rate of collection, the data received was also more variable, and resulted in frequent removals thereby requiring a much larger number of participants. The issues surrounding methods for participant recruitment and additional performance-based methods to incentivize participants persists and should be explored in future work.

The reader will recall that some of our results are the opposite of what the theory supposes. That is, the Sunk Cost Fallacy research says that people who invest more resources in a difficult project should be *less* willing to switch to an alternate. Under the effects of the Sunk Cost Fallacy, people overvalue the invested resource and discount the future benefits of choosing an alternative. They stick with what they started. However, these results indicate that this was not the case in our study. Arechar and Rand, (2021) presented research that might help to explain this phenomenon. The authors investigated the effects of COVID-19 on Mturk subject pool demographics in 23 studies ran from February through July 2020. Along with a shift toward more male, non-white, Republican leaning participants, Arechar and Rand (2021) reported a significant reduction in attentiveness. Important differences were attributed to an influx of new workers. Considering this evidence, along with the economic anxiety related to on-demand workers (Condon & Wichowsky, 2022), we reason that for our participants, the greatest motivator for decision-making was switching when the task required too much attention and effort and/or the switch/stay decision would reduce time spent on task.

Cyber adversaries also experienced the effects of the COVID-19 pandemic, but not in the way most people did. At best, evidence shows attackers took advantage of the world-wide turmoil and increased phishing schemes and targeted health-related websites. As global anxiety soared, these criminals took advantage. At worst, industrial supply chains were stymied leading to fuel, food, and building material shortages. Attacks on our American political system infiltrated the internet with fake news and Capitol Hill was breeched by every-day citizens who believed the foreign cyber meddling.

Survey Response Lessons Learned. Drawing from the survey responses, we begin to see rich decision-making processes that may shed light on these results and pave the way for future improvements in the experiment design. For example, some participants were influenced by the sunk cost fallacy, while others were attentive to the switch portal presentation and made the choice to conserve resources, others appear to have made decisions based on other factors. These factors included judgements influenced by the game storyline (To catch the thief, "*I switched the first time and it didn't work"*), or personal motivation *(*"…staying on one path/task feels more satisfying."*),* level of engagement *("I was bored")* or to avoid effort (*"If it is difficult… I would choose another server"*). This suggests that using switch choice as the sole metric of sunk cost fallacy is complex, and these various factors should be more carefully explored experimentally.

We found most participants reported enjoying the experiment, felt solving the cyphers was moderately easy, and switched because they believed it would be faster (again a key goal of MTurk workers). The free-response survey suggests that the cypher difficulty had a stronger influence on switching than uncertainty. It is possible that given participant motivations, the effects of uncertainty and difficulty occasionally worked against each other, and produced inconsistent results related to individual differences in the tolerance to uncertainty measure, effort avoidance, and the realized value of time to complete the HIT (Table 37). Future research is needed to understand whether this is a population-based issue from using MTurk workers, or some other combination of issues including the experiment design, materials, or presentation as discussed above.

Variables	Conditions		Interactions	Ruling Factor	Sunk Cost Fallacy (Portal Switch)
Uncertainty	Hard	Uncertain	Competitive	Effort Avoidance	Switch
+ Project	Hard	Certain	Cooperative	Effort Avoidance	Switch
Completion	Simple	Certain	Cooperative	Certainty	Switch
	Simple	Uncertain	Competitive	Uncertainty	Stay

Table 37. Competitive and Cooperative variables.

One suggestion is that our population sampled came with some unique aspects in their psychological states, and that this could have influenced our results. We believe the response pattern in the Intolerance to Uncertainty Scale, in particular, to be a factor of participants' general outlook, and not due to the experimental conditions although a pre-test was not performed, and no comparison can be made.

Participants' response patterns in the choice surveys mirrored the Kahneman and Tversky (1979) questionnaire, with one exception. These results generally suggest participants in our experiments tended to prefer options that appear to be more certain. However, we did not find consistent results between uncertain and certain conditions in our experiment. From this, it appears that making a rapid decision on a simple, two-choice questionnaire is not equivalent to making a similar decision amid a task that requires more mental effort and/or our switch prompt did not clearly convey the information to make an appropriate choice. That is, we theorize that perhaps if the switch opportunity message in our experiments conveyed more certainty participants may have chosen to switch more often.

Exploratory analyses demonstrate the mechanics of the experiment worked as expected (switching reduced resource use, difficult cyphers increased resource use). However, these analyses did not shed much light on the decision-making related to our manipulations of certainty, project completion, and effort. These analyses provide a granular look into resource utilization that will be useful for future research.

The manipulations in this experiment did not create the effects we had anticipated. From the results in Experiment 1, we believe the Uncertainty variable was a stronger influence that may have counteracted with the Project completion variable. It is possible that a similar situation occurred in Experiment 2, where the two variables cancelled out any significant difference between conditions.

Attack Surface

The Cypher platform was developed as a proxy for the mental effort required of an attacker to breach a network: decrypting passwords to advance through abstracted data servers in the pursuit of accomplishing a goal. Bringing the lessons learned from Cypher, the Attack Surface experiment was designed to also test the variables of certainty, project completion, and task difficulty. We also implemented changes to the switch message and limited trials.

The Attack Surface (AS) paradigm represents a more cyber realistic environment in which participants will assume the role of a cyber attacker with a mission to infiltrate a large, corporate network to steal valuable information from the organization's data server. With a limited number of resources, participants will perform tasks to navigate through the secure subnets in the network. Subnets contain three types of hosts: personal computers, servers, and decoys. Tasks will simulate network reconnaissance to discover important details about each node, attack nodes to gain points and to advance deeper into the network. Multiple decision points throughout the network path measured the effects of the sunk cost fallacy.

The following presents the application of lessons learned to improve experimental design for each of the three variables.

Certainty

The storyline was simplified and removed from decision points. Focusing on task relevant information, the certainty manipulation was reduced from a paragraph of text displayed in Cypher to three simple lines, presented as an exact or estimated subnet resources (i.e. exact/estimated coin and turn cost, point gain) required to gain points and access the next subnet; performing simple math to compare each path is not required.

Project Completion

The Early and Late intervals were removed in favor of measuring project completion using a more cyber-realistic *forward progress* into the network. Rather than directly manipulating this variable, the Attack Surface design also allows for player-driven movement and choice throughout a network.

Difficulty

Previous research states that when a task is difficult the Sunk Cost Fallacy affects decisions more than when the task is not. However, specifically defining a difficult task is vague. In Cypher, difficulty was presented as mental effort. In Attack Surface, task difficulty was implemented as the number of resources required to successfully attack each system in a subnet. While mental effort is still required, it is less obvious how it is being used, and is more likely to be engaged by higher-level processes including strategic thoughts as participants weigh options and decide whether to attack or scan different machines in the network.

Switch Message

Cypher presented one instance to switch in each trial. We speculate that the novelty between the two trials came into play for participants who changed their decision between trial 1 and 2, in that curiosity could lead people to do something different rather than being more influenced by sunk cost. In Attack Surface, participants may encounter three opportunities to switch and the encounters themselves are far more realistic in that they represent real changes in capability for the attacker (e.g., the discovery of a ‘key’ credential that allows new access in another part of the network). Ineffective intervals between the early and late message presentation in Cypher was also remedied by more natural variation in timing.

Additional Trials

In Cypher, the brief practice session to solve one 5-character cypher and two performance trials in Cypher may not have been ideal to capture consistent effects. Attack Surface contains a ten-minute practice session and three more involved performance trials. We hypothesize more exposure to the experiment tasks will provide more consistent effects and greater ease of interpretation.

From Theory to Applied Research

From the perspective of progress decision scenarios, the Cypher experiments present the first interactive platform specifically designed to measure the effects of decision-making bias. Progress decisions, where choices are strung together over time, have been researched from a historical standpoint where data pulled from large projects was analyzed. From our results, we suggest that effect of the Sunk Cost Fallacy is an inherent decision-making bias that can be measured within a progress decision, task-oriented experiment. The crosstabulations for experiment 1 and 2 demonstrate that overall, irrespective of condition or experiment, the majority of participants *always chose to stay* on the starting portal and is similar between experiments. This is the case even though our manipulations did not significantly work, as planned. Beyond the limitations of our experiment design, our results do show trends that are supported by the foundational theory. Some of the difficulty in doing this type of research is that beyond Kahneman and Tversky's Prospect Theory and Arkes and Blumer's key research on the SCF, the subsequent research is fractured and contradictory, particularly related to contextual elements surrounding the effects of SCF. For example, our literature review showed disagreement regarding the effects of uncertainty, project completion level and the types of resource investment that underly the effects of the sunk cost fallacy on decision-making. Furthermore, Prospect Theory was originally about behavioral economics, but has since been rather haphazardly applied to various situations (e.g., interpersonal relationships, medical diagnoses, marketing). Building upon tenants of Prospect Theory, Arkes and Blumer extended the SCF theory to identify money, effort and time as investment resources, but left effort ill-defined. To our knowledge, empirical guidance for testing the SCF in a progress decision scenario is non-existent. This project provides initial groundwork into investigating the complexity of progress decision-making within a cyber environment. In this work, we have attempted to bring some ecological validity into a controlled laboratory experiment.

Extending Foundational SCF Theory

In this project, we have moved the SCF from utilization decision-based research to progress decision-based research in a use case context: in a cyber environment. As we continue forward, SCF research must also take a more holistic approach to human decision-making — considering the emotional, social, and cultural motivation that cohabitates the realm of decision-making. Applying the findings from our SCF research to target attacker groups like foreign nation states, terrorists, and industrial spies and organized crime groups (Cybersecurity and Infrastructure Security Agency, 2022) could be an addition to the cyber deception methods currently employed.

Emotional Motivation

Decision-making tends to be affected by one's current emotional state (Schwarz & Clore, 2003), previous experience in similar situations (Schwarz, 2012), and with representations of objects and people associated with positive and negative memories (Kahneman, 2003a; Slovic et al., 2002). For example, Dijkstra and Hong (2019) measured participants' affective reaction, between and within subjects, caused by sunk-costs scenarios (invest or non-invest) and the subsequent decisions. The results showed the invest scenario elicited a stronger sunk cost effect and was associated with more negative emotional reaction. A mediation analysis demonstrated that the strength of the sunk cost fallacy was mediated by emotional reaction in the two scenarios. That is, when participants believed their decision was reasonable (i.e., justified), the negative feelings of throwing away good money (e.g., waste) were reduced. In professional red teamers, Ferguson-Walter, et al., (2021) and Shade, et al., (2020) demonstrated effective use of cyber and psychological deception to create emotional effects that slowed and deterred forward progress in malicious attacker activities.

Personal and Social Motivation

Prior research suggests the importance of personal responsibility (Arkes & Blumer, 1985; Arkes & Hutzel, 2000) and social accountability (Bazerman et al., 1984). Accountability for choosing to initially invest in a project is a strong motivating factor when decision-makers fall victim to the SCF. Leaders do not want to lose credibility with co-workers for making a poor decision and so choose to continue in a failing project, all the while hoping for a miraculous turn of events to save the project and their reputation. People choose to stay the course because they want to avoid being seen as unable to follow through with commitments, unreliable to finish a job, wasteful and/or unintelligent. Given the teaming nature of some cyber attackers, this social element could be a powerful lever in disrupting attackers alongside other team biases (C. J. Johnson et al., 2022).

Cultural Motivation

A large body of research on cultural differences describes two main dimensions: individualistic or collectivistic societies (Yates & de Oliveira, 2016). An individualistic culture places greater importance on the individual person as an independent, unique person with free agency for self-expression, responsible for themselves and a close-knit social group over those of outside groups. Individualism tends to coincide with looser social norms and enforcement of breaking them. A collectivistic culture places great value on the whole as individuals are expected to fit in, pursue harmony and consensus. Collectivism tends to coincide with more rigid cultural norms with high penalties for stepping outside the rules. This could influence some biases and their induction; for example, Weber and Hsee (2000) reported that loss aversion appears less in collectivist cultures because a strong social network could provide assistance if a risky venture turned out poorly. Wang et al., (2017) studied 53 countries and found that individualism was positively correlated with loss aversion. For example, Eastern European cultures were high in country-wide individualism and loss aversion whereas African cultures were low.

Other effects may occur as well. For example, behavior that results in a gain will update the reference point from which future decisions are made and thus, risky behavior might increase with subsequent gains, and less risk avoidance for potential loss. This *reference point updating* appears inconsistent across cultures; Arkes et al., (2010) found that following a beneficial trade of stocks, participants from China and Korea demonstrated less loss aversion than participants from the United States.

Finally, there do appear to be cultural differences in dealing with uncertainty. While Wright (1981) did not find cultural differences in uncertainty between British, Hong Kong, Malaysian, and Indonesian student samples, Shuper et al. (2004) investigated uncertainty orientation in Canadian and Japanese university students and found Japanese students exhibited higher uncertainty avoidance than Canadian students. Similarly to the work done on the Intolerance to Uncertainty scale by Hong and Lee (2015), avoidance fell into two categories: inhibitory and prospective. Those who exhibit the inhibitory aspect tend toward passivity, avoidance and disengagement, while those who exhibit the prospective aspect tend to seek more information in the attempt to reduce uncertainty. We hypothesize that regardless of the reaction type to uncertainty, both are a defensive advantage. Those who avoid uncertainty will be deterred, choosing cyber activities that are more certain. Those who take the time to seek out more information will be delayed, giving defensive teams more time to detect and stop malicious attacks.

More research in determining the characteristics across cultures will help characterize attackers in meaningful ways.

Application to Cyber Security

Cyber adversaries are a ubiquitous presence across the globe (Georgiadou et al., 2021). As the COVID-19 pandemic took hold, cyber criminals took advantage of societal and economic unrest, and played upon uncertainty, misinformation. “From February to March 2020, a 569% growth in malicious registrations, including malware and phishing and a 788% growth in high-risk registrations were detected and reported” (Interpol, 2020).

Most methods for detecting and stopping malicious actors focus on collected intelligence such as the tools, tactics, and procedures (TTPs), target sectors, and associated malware used by specific threat groups (Pennino & Bromiley, 2019). These data contribute to various publicly attacker profiles and matrices (Strom et al., 2018). Interestingly, Bada and Nurse (2021) provided a systematic review of 39 papers from 2006-2020, profiling cyber-criminals. These works contain profiles to identify “behavioral tendencies, personality traits, demographic … and geographical variables” (p. 1). However, many adapted secondary data from other domains. Geographical variables begin to broach cultural aspects associated with cyber criminality, but algorithms search for serial offenders and location masking capabilities (i.e., VPN) render geolocation problematic. Furthermore, decision-making research within the adversarial cyber domain tends to focus on group dynamics (e.g., structure, conflict and division of labor), (Rege et al., 2017) rather than the cognitive processes involved in every-day choice and judgment. Decision-making and associated limitations, as presented in this paper, are an unexplored avenue. We have provided evidence that leveraging these limitations had an effect of delaying forward progress. This project provides a novel proactive strategy that focuses on human actors.

Adding the defensive technique of psychological deception on top of cyber deception (e.g., honey-things), might provide for the next generation of network protection. Crafting an adaptable defense strategy should consider the limitations of the human mind. In the available on-demand subject pool, we have demonstrated the SCF is a ubiquitous phenomenon.

CHAPTER 6

CONCLUSION

Understanding decision-making biases in cyber adversaries is a critical component to the evolution of defensive techniques in cyber warfare. Cyber security is a socio-technical system in which human operators make critical decisions that can be influenced by biased thinking. Biases operate beyond conscious awareness, making the decision-maker a possible victim of prevalent human limitations (Arkes, 1991; Fischoff, 1981; Wilson et al., 2013).

Our endeavor was to validate the foundational research about the SCF within an interactive cyber task. We began with a simplified cyber construct to answer our research questions and substantiate our hypotheses. The results informed the design of Attack Surface. Although our manipulations did not consistently create hypothesized effects, the results demonstrated that the Sunk Cost Fallacy exists and can be measured in scenarios that are beyond the theoretical foundation primarily based in behavioral economics and simple, single-decision scenarios. The experiments also uncovered the complexity of decision-making biases in a cyber task-oriented experiment. We learned about several of the surrounding factors when the Sunk Cost Fallacy does or does not occur. Building upon the foundational theory, we designed a novel approach to measure the Sunk Cost Fallacy and extended the previous research by balancing laboratory controls with ecological validity. Offering methods for application, these experiments have provided valuable insight into experimental improvements and presented guidance to develop robust methods to systematically study, elicit, and apply the sunk cost fallacy to modern defense systems.

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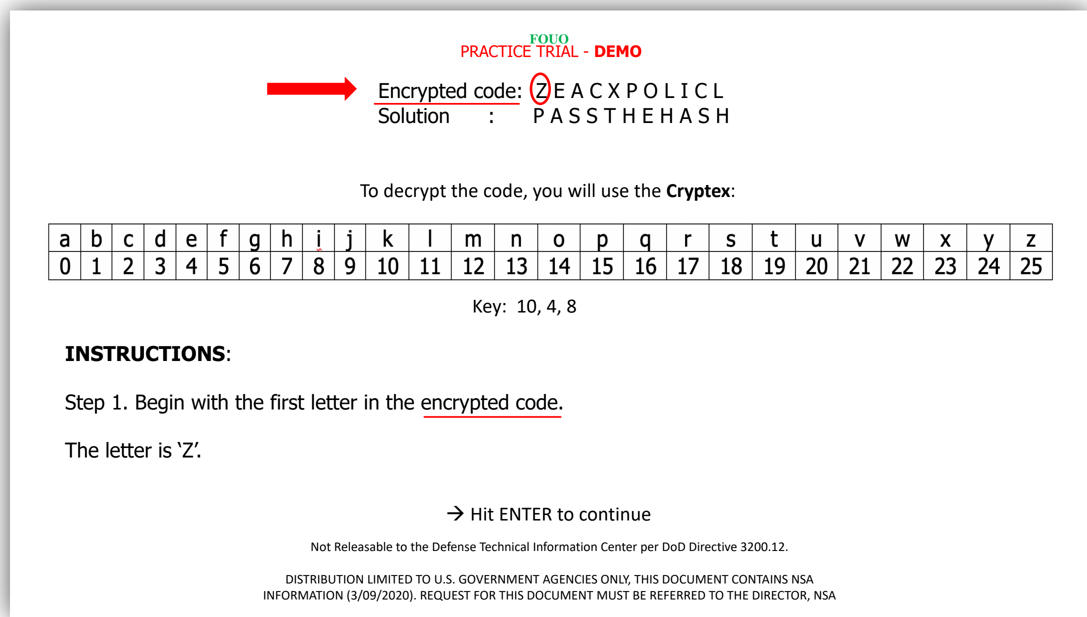
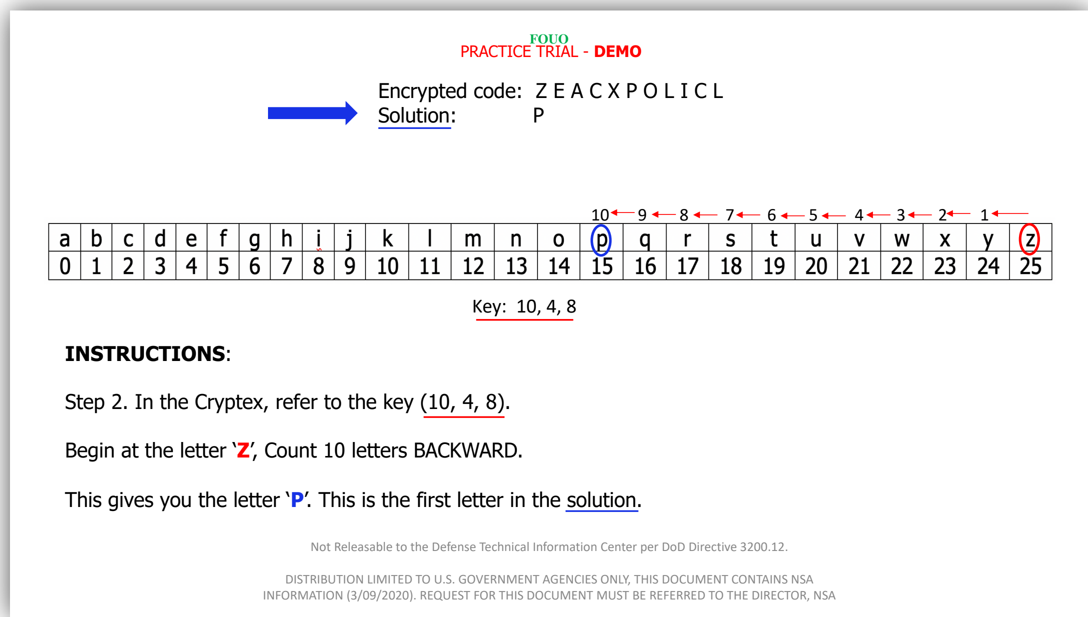
APPENDIX A

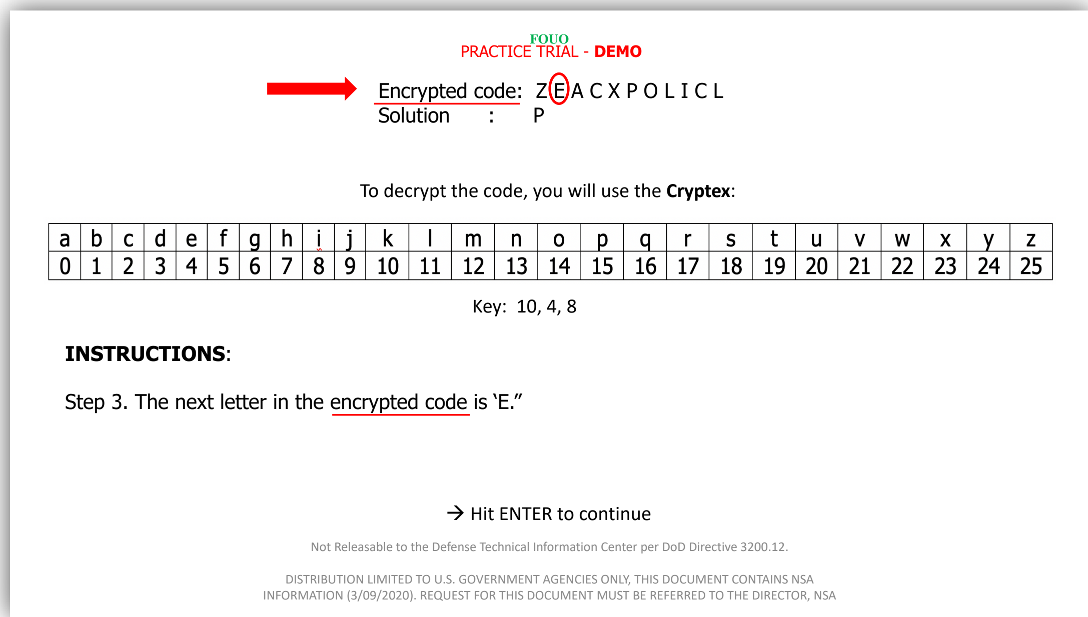
CYPHER WIREFRAME



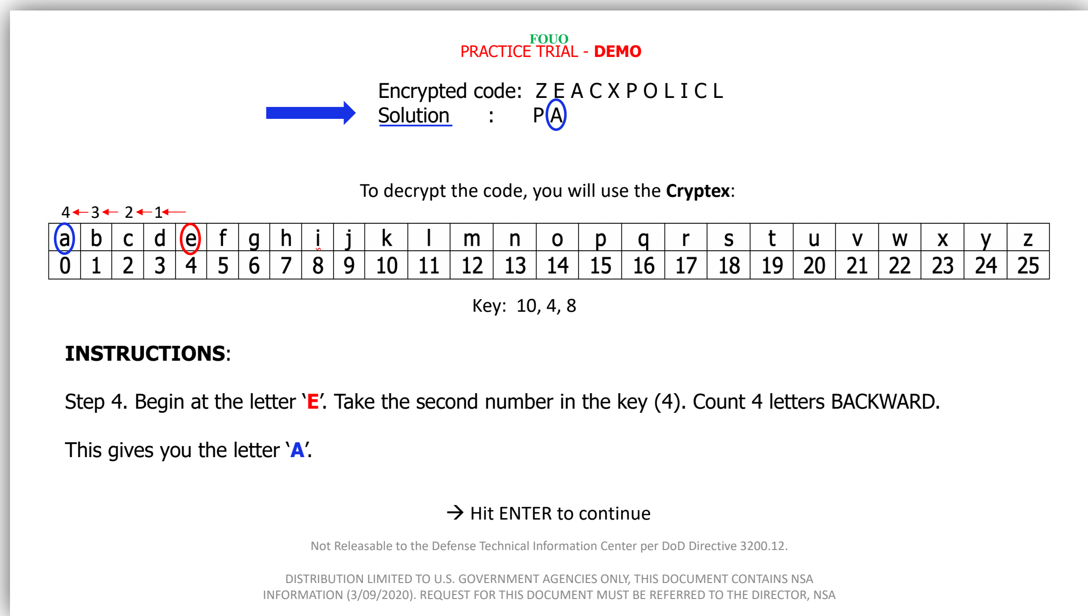
Practice Trial demonstration, code decryption. Step 1.



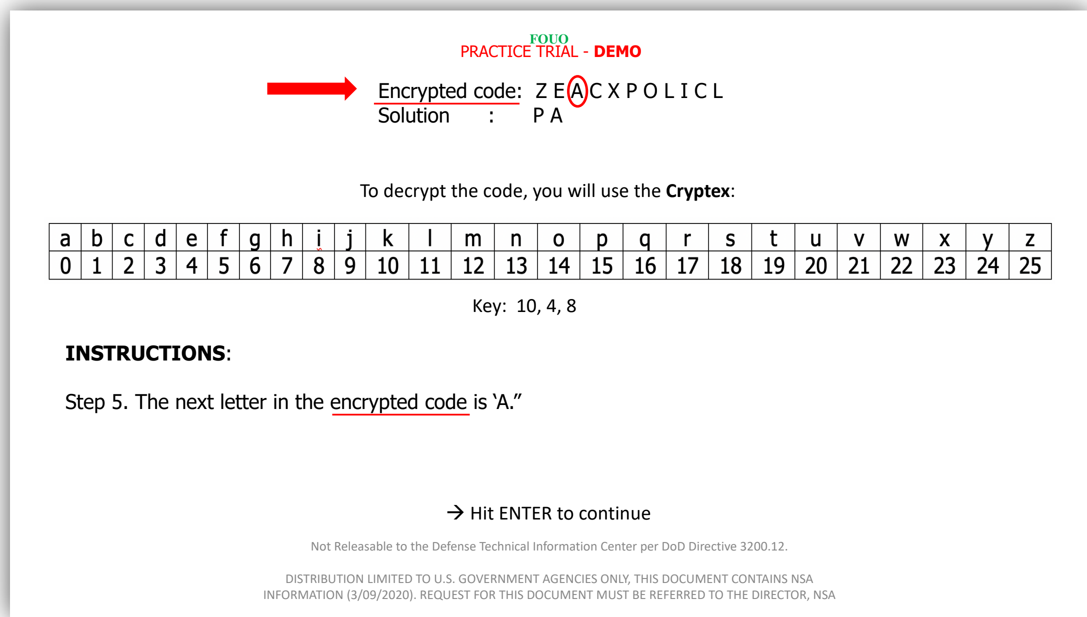
Practice Trial demonstration, code decryption. Step 2.



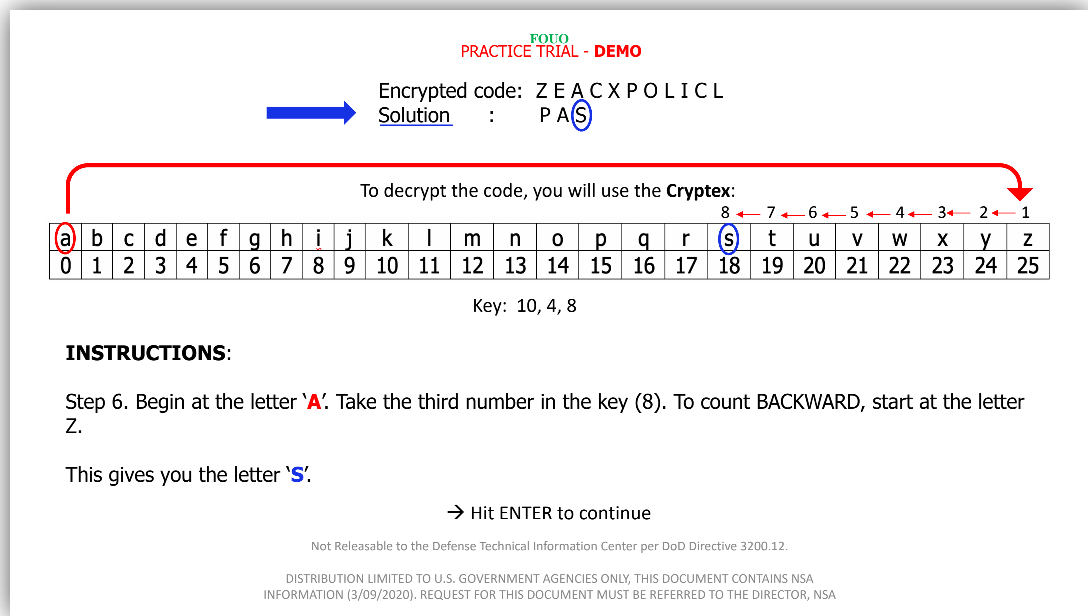
Practice Trial demonstration, code decryption. Step 3.



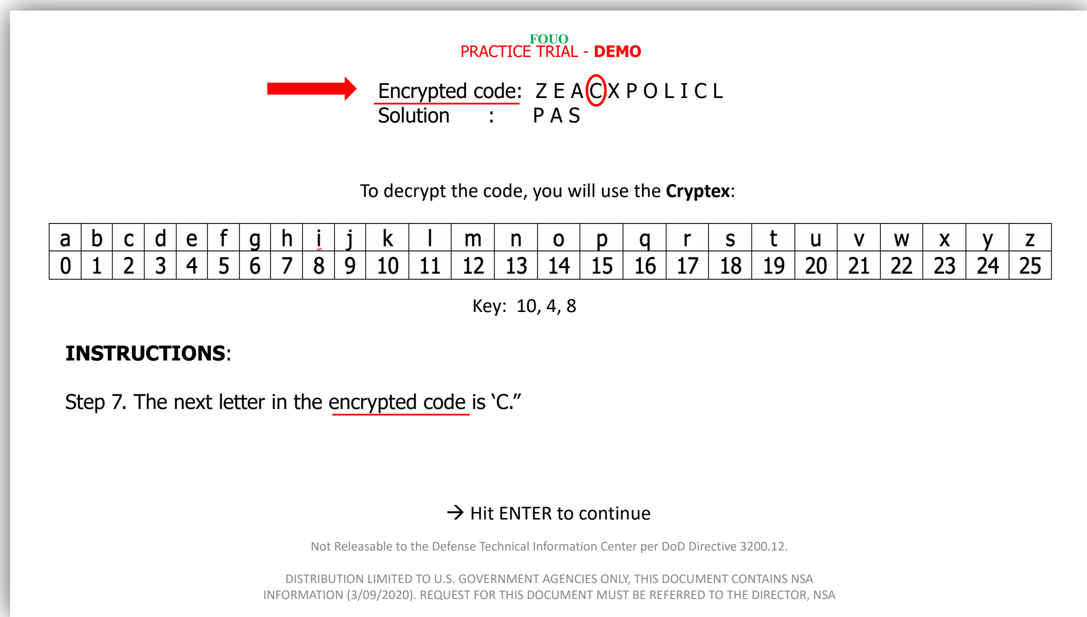
Practice Trial demonstration, code decryption. Step 4.



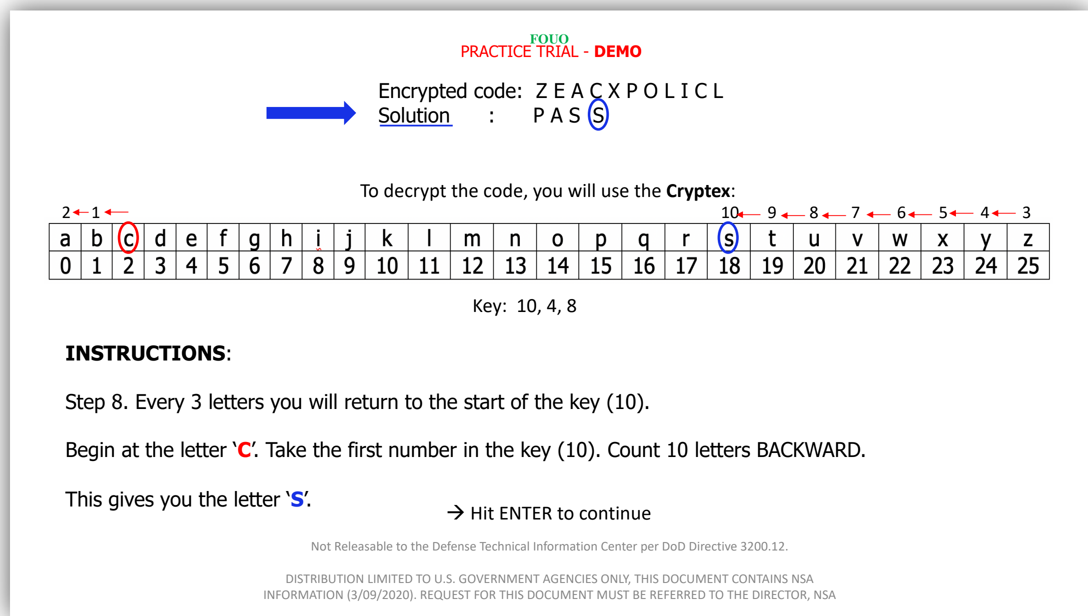
Practice Trial demonstration, code decryption. Step 5.



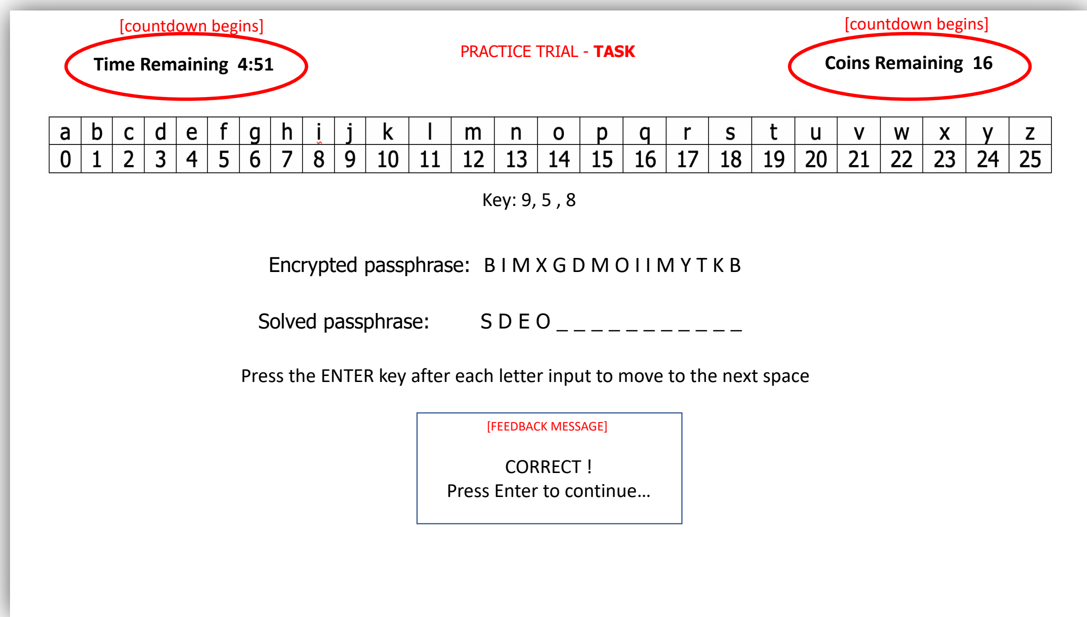
Practice Trial demonstration, code decryption. Step 6.



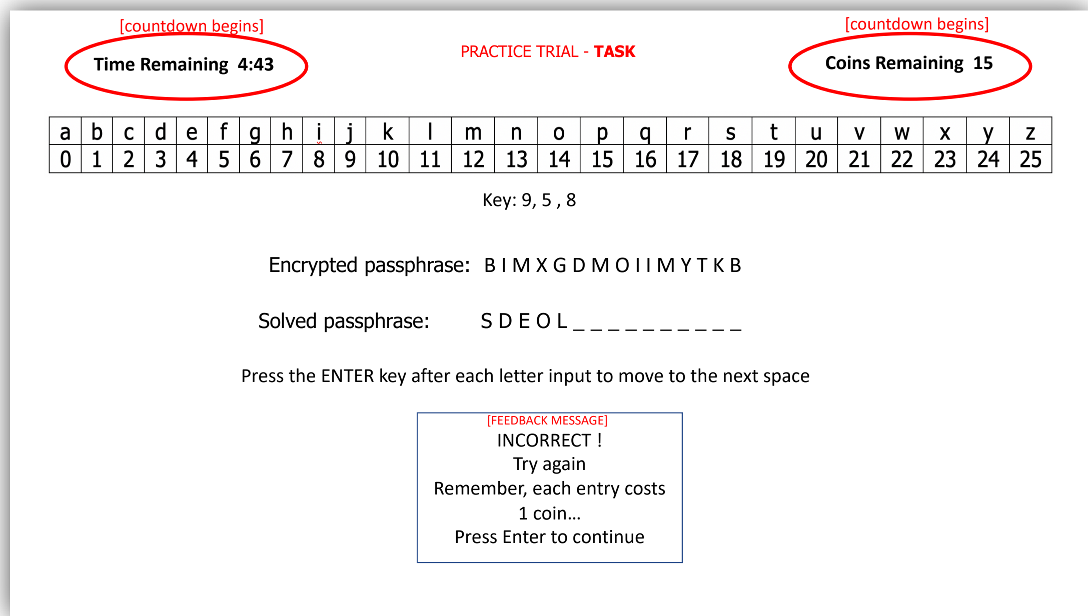
Practice Trial demonstration, code decryption. Step 7.



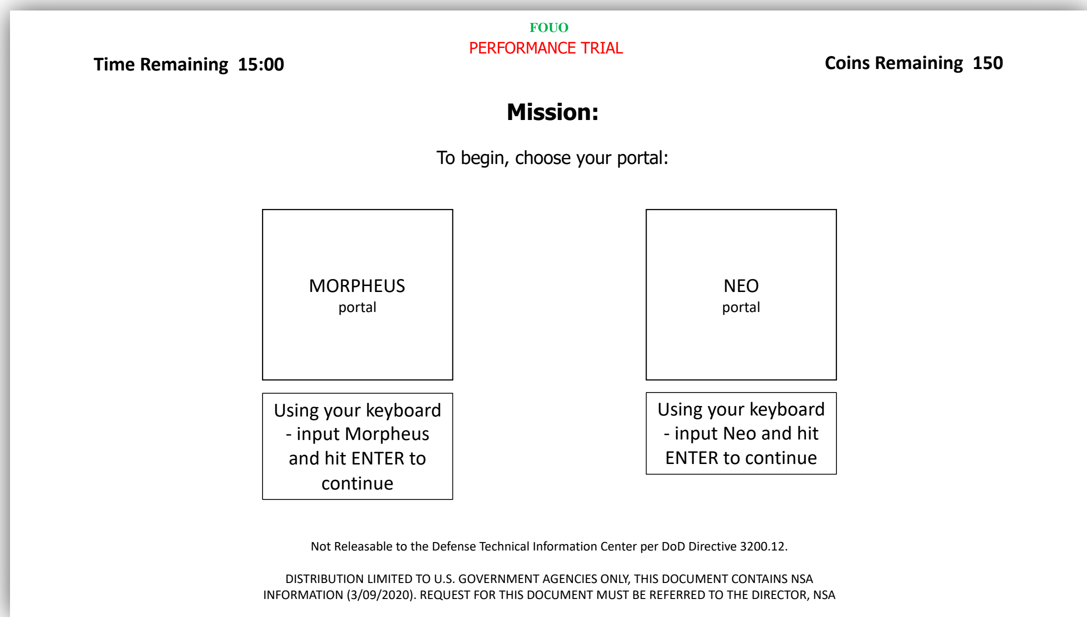
Practice Trial demonstration, code decryption. Step 8.



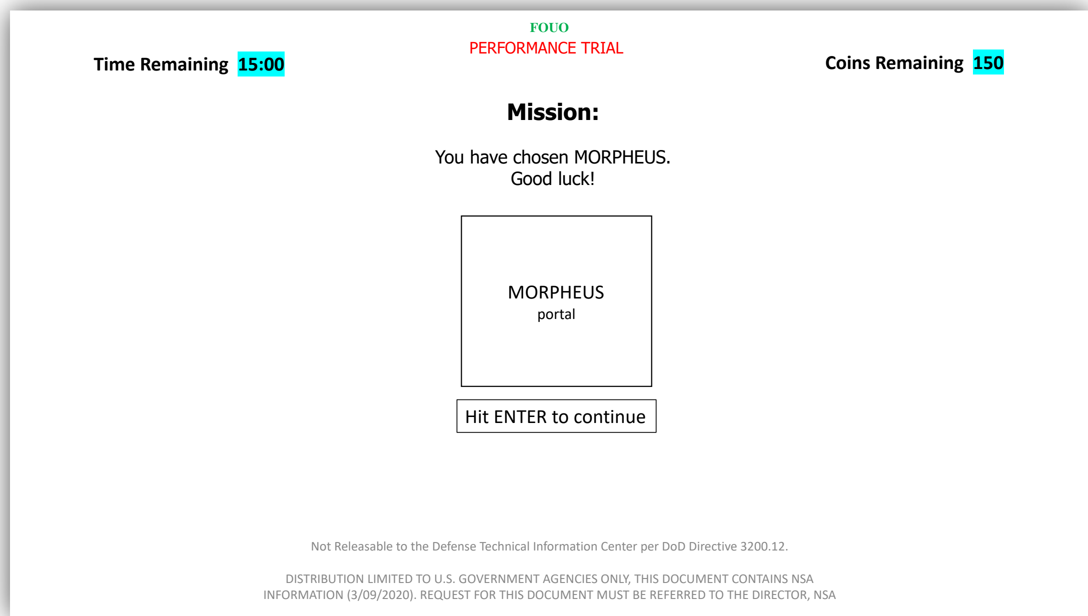
Feedback message: Correct entry.



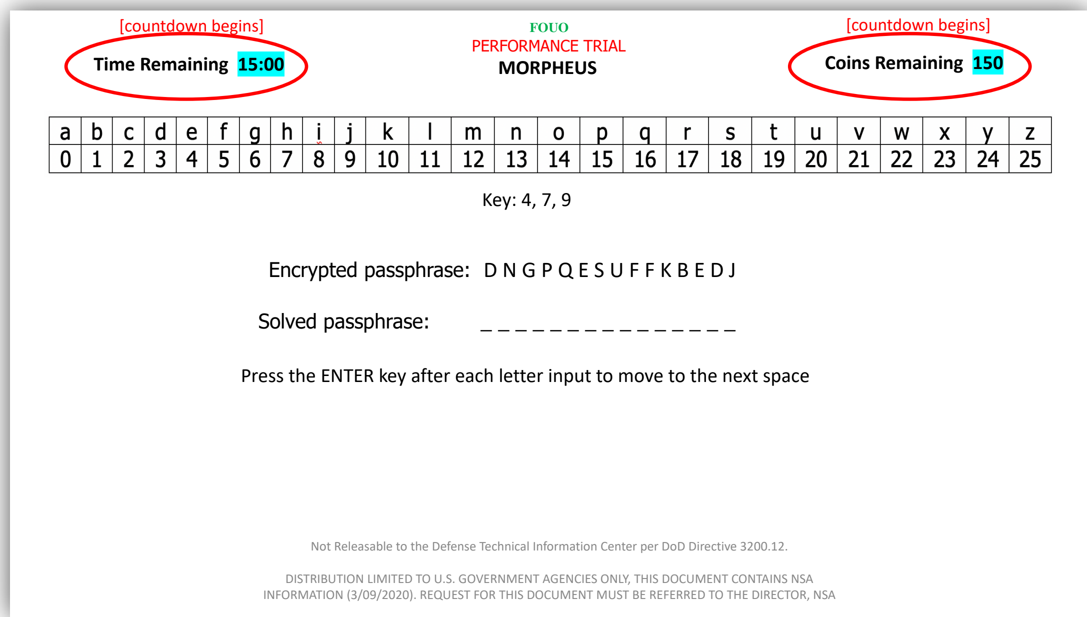
Feedback message: Incorrect entry.



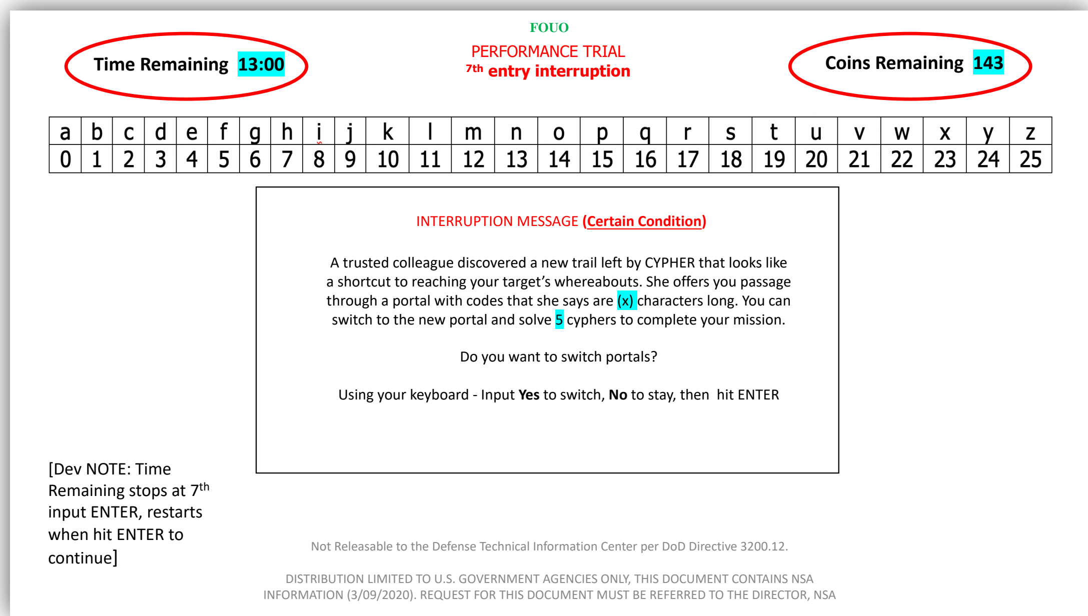
Portal choice.



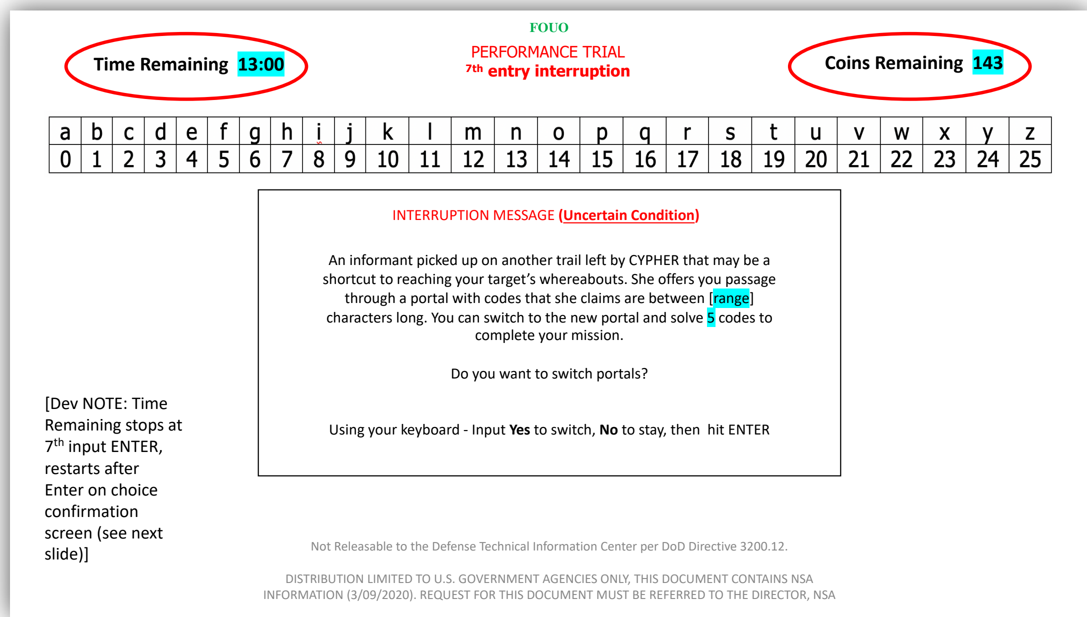
Portal choice feedback.



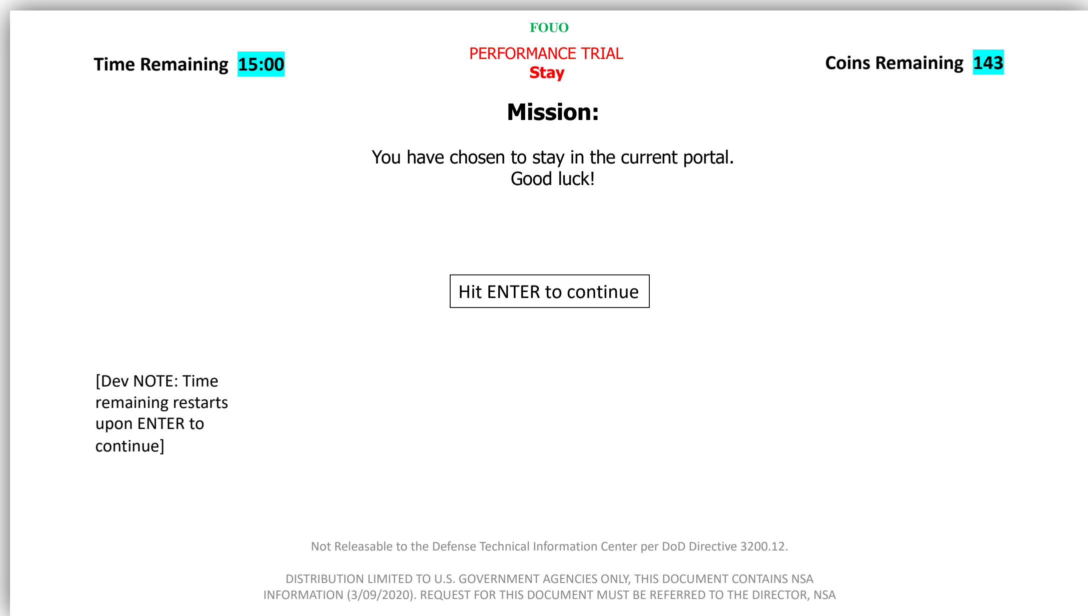
Performance Trial



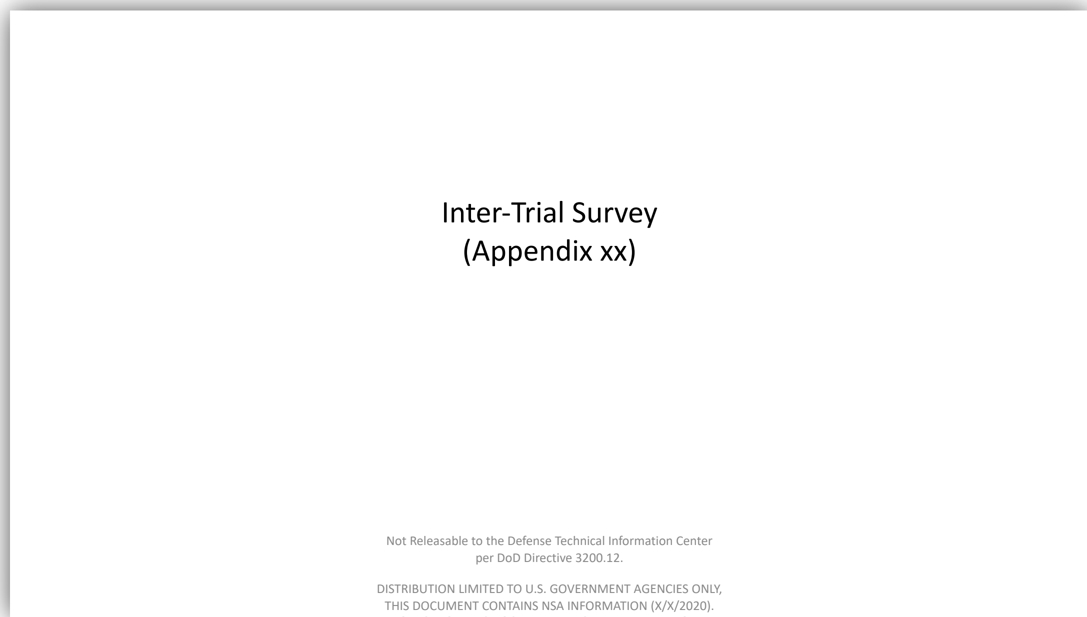
Interruption message - portal switch, certain condition.



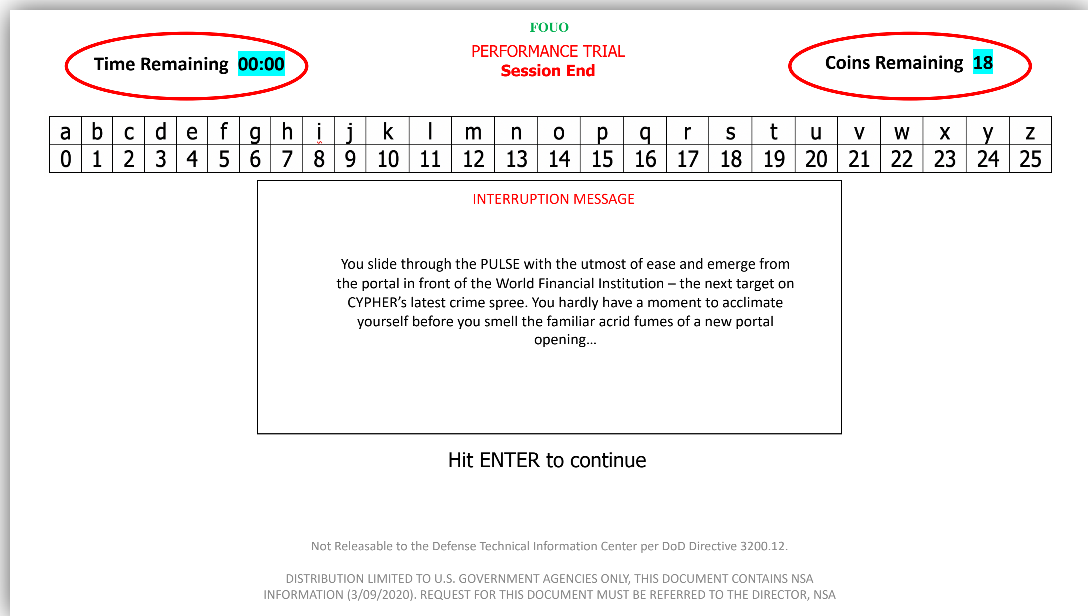
Interruption message - portal switch, uncertain condition.



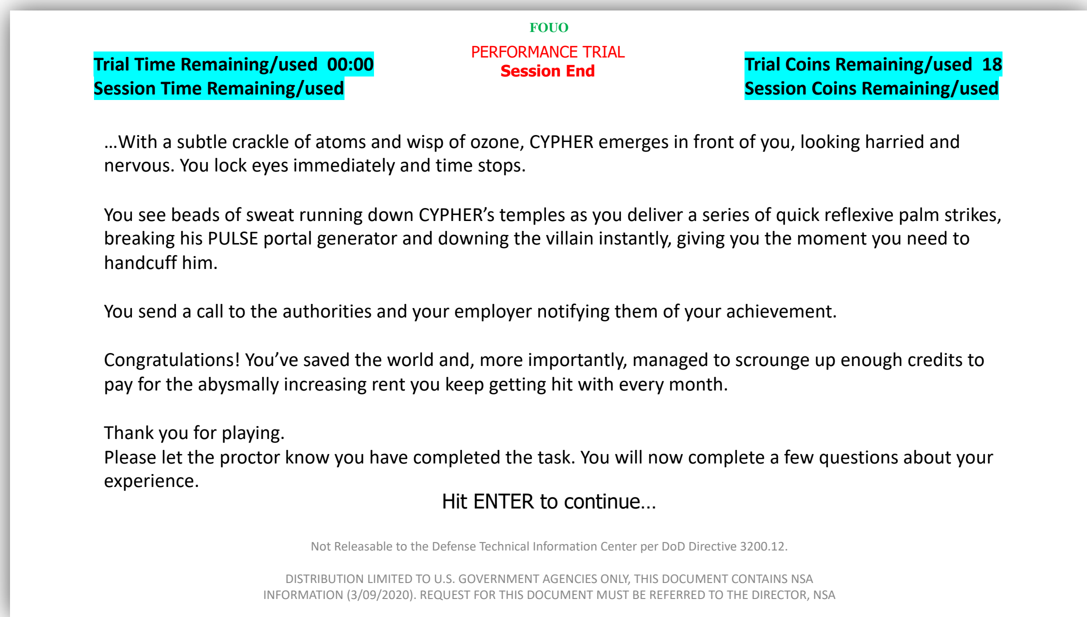
Portal choice feedback message.



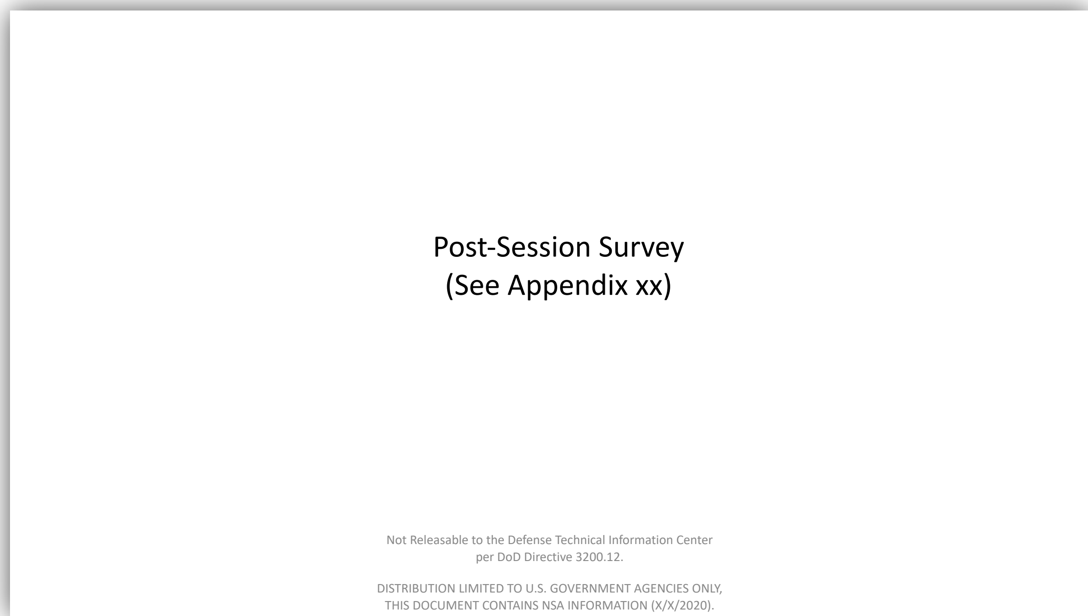
Inter-Trial Survey



Trial/Session completion.



Session End



Post-Session Survey.

APPENDIX B

CYPHER INTER-TRIAL SURVEY

(This short survey occurs between the 1st and 2nd trials)

Multiple Choice Questions. Please select ONE answer for each question.

1. Why did you stay/switch portals?
    a. I thought it would be faster
    b. I thought it would be easier
    c. I was bored
    d. I don't know
    e. Other [Free Response Field]

2. Did you enjoy this task?
    a. Yes
    b. No
    c. Indifferent
    d. I don't know
    e. Other [Free Response Field]

3. How difficult would you say this task is?
    a. Easy
    b. Moderately easy
    c. Moderately hard
    d. Hard
    e. Other [Free Response Field]

4. Do you know modular arithmetic?
    a. Yes, I use it every day
    b. Yes, but I don't really ever use it
    c. I learned about it
    d. I don't know what that is
    e. Other [Free Response Field]

APPENDIX C

DEMOGRAPHIC AND TASK QUESTIONNAIRE

Demographic information

1. Occupation
2. Highest degree completed
3. Age
4. Gender

Task-Related Questions

1. Why did you choose to participate in this experiment?

2. How did you choose to start on one server, over the other? List any details or thoughts you had in order.

3. If you ever chose to **stay** on the current server when given the choice to switch, how/why did you make that decision? List any details or thoughts you had in order.

4. If you ever chose to **switch** to the other server during this experiment, how/why did you make that decision? List any details or thoughts you had in order.

5. What are your top three hobbies?

6. Do you ever play the lottery?

7. If you won the lottery, what would you do?

APPENDIX D

CHANCE QUESTIONNAIRE

The following is a series of comparison questions. We would like you to choose between two hypothetical outcomes. Circle the one answer for each pair that you would prefer. Choose between the following:

Question 1.
a. 50% chance of winning a 3 week, all expenses paid vacation to 3 locations of your choice
b. Guaranteed 1 week, all expenses paid vacation to 1 location of your choice

Question 2.
a. 5% chance to win a 3 week, all expenses paid vacation to 3 locations of your choice
b. 10% chance to win a 1 week, all expenses paid vacation to 1 location of your choice

Question 3.
a. 45% chance to win $6,000
b. 90% chance to win $3,000

Question 4.
a. 1% chance to win $6,000
b. 2% chance to win $3,000

APPENDIX E

INTOLERANCE OF UNCERTAINTY SCALE (SHORT)
CARLETON, NORTON, & ASMUNDSON, 2007

Please circle the number that best corresponds to how much you agree with each item.

	Not at all characteristic of me	A little characteristic of me	Somewhat characteristic of me	Very characteristic of me	Entirely characteristic of me
1. Unforeseen events upset me greatly.	1	2	3	4	5
2. It frustrates me not having all the information I need.	1	2	3	4	5
3. Uncertainty keeps me from living a full life.	1	2	3	4	5
4. One should always look ahead so as to avoid surprises.	1	2	3	4	5
5. A small unforeseen event can spoil everything, even with the best of planning.	1	2	3	4	5
6. When it's time to act, uncertainty paralyses me.	1	2	3	4	5
7. When I am uncertain I can't function very well.	1	2	3	4	5
8. I always want to know what the future has in store for me.	1	2	3	4	5
9. I can't stand being taken by surprise.	1	2	3	4	5
10. The smallest doubt can stop me from acting.	1	2	3	4	5
11. I should be able to organize everything in advance.	1	2	3	4	5
12. I must get away from all uncertain situations.	1	2	3	4	5

APPENDIX F

CYPHER - ACTION DEPENDENT NARRATIVE

Storyline outcome based on possible decisions and actions – Success, Failure in solving a trial

Opening Introduction:

- WELCOME TO THE PULSE! You stand before a pair of whirling portals, curiously cut into the fabric of your reality. They radiate with energy, assaulting your senses with otherworldly sights, smells, and sounds. The fantastical realm holding the PULSE – the evolved internet of your time – is hardly new to a rogue-hunting agent as yourself, but it never loses its glamour. You've been employed to capture a sinister criminal known only as CYPHER.
- CYPHER is a clever thief who can maneuver through the PULSE as easily as yourself, but he's been getting sloppy since his notoriety has escalated. You've managed to dredge up a couple of coded addresses that, when tuned into your digital Cryptex with letters and numbers (and a modest amount of credits), promise to take to you to CYPHER's next location. You're familiar with both routes; each will take around the same time.
- Rifling through your pockets, you find about 150 credits – not nearly enough to pay the rent, but plenty to keep your Cryptex running. Though the bounty to catch CYPHER is large enough to keep you afloat for many months, you won't be paid until you capture him. Use your remaining funds wisely and don't waste time or he'll get away!"
- Using a Cryptex, you will need to solve 5 codes on one of 2 available portals. You will choose where to begin. You will be given the opportunity to change portals but will not be able to return to the previous portal. Codes vary in length. Some codes may be long (up to 9 characters), while others may be short (3 characters).
- Each character entered in the code will cost 1 coin. You must enter one letter at a time. You cannot skip around. Incorrect entries will cost you 1 coin each. Your starting coin bank contains 150 coins. You have 15 minutes to solve 5 passphrases.
- Only use as many resources as you absolutely need to complete your mission. An on-screen count down timer and bank will keep track of remaining time and coins. Your first task will be to practice using the Cryptex to **solve 1 cypher**.

Practice Trial:

- [demonstration and walk through, no narrative content]

Performance Trial:

- To begin, choose your portal (Portal 1, Portal 2)
- You have chosen Portal (x). Good luck!

Portal Switch Message (certain condition):

- A trusted colleague discovered a new trail left by CYPHER that looks like a shortcut to reaching your target's whereabouts. She offers you passage through a portal with codes that she says are (x) characters long. You can switch to the new portal and solve 5 cyphers to complete your mission. Do you want to switch portals?

Portal Switch Message (uncertain condition):

- An informant picked up on another trail left by CYPHER that may be a shortcut to reaching your target's whereabouts. She offers you passage through a portal with codes that she claims are between [range] characters long. You can switch to the new portal and solve 5 codes to complete your mission. Do you want to switch portals?

Portal Switch message:

- You have chosen to switch portals. Good luck!

Portal Stay message:

- You have chosen to stay in the current portal. Good luck!

Success First Trial:

- "You've at last reached end of your passage through PULSE. Your mind goes fuzzy with the overload of physical sensations that comes with your body's cells realigning back into physical space. Once the screaming of your nerves and the ringing in your ears silences, you scope out your surroundings. Empty caches and piles of scattered papers are illuminated by the nearby monitors flashing CYPHER's logo; one you are all too familiar with. Drat, you were too late! You deploy your PULSE tracer drone to scan the room for possible travel routes recently opened up. It quickly feeds a list to your heads-up display. You quickly recognize one – the World Financial Institution -- that fits the pattern of CYPHER's previous hits."
- "Briefly, you inform your employer about your progress. Your success in anticipating CYPHER's movement patterns seems to feed their desperation to catch the thief, as they quickly wire you some additional funds to ensure the criminal is caught. Never one to turn down early compensation, you pocket the credits, share a brief word of appreciation to your benefactor, and continue with your work."

- “You know of two routes to get to the World Financial Institution. Select one quickly, and you might just beat CYPHER to the punch next time.”

Failure First Trial - Run out of money:

- “Your mind fires a million decisions a second as you twist, jump, and collapse the remaining legs of your trip into one blur of movement through PULSE. Your liberal use of credits may have dried up your funds, but you reach your destination regardless in a feat of true aethereal mastery.”
- “Your Cryptex fizzles with the scant remnants of the credits you’ve plunked into it. It whines as it threatens to dump you out at the next nearby drop point. Focusing your will into the system, you manage to get it to bypass a few checks to ensure you get to your destination. Whew! You’ll be paying for that tomorrow with a few heavy fines you couldn’t afford…but those problems will be a drop in bucket if you manage to get the reward money for catching CYPHER.”
- “You manifest back into the world from PULSE. Your mind goes fuzzy with the overload of physical sensations that comes with your body’s cells realigning back into physical space. Once the screaming of your nerves and the ringing in your ears silences, you scope out your surroundings. Empty caches and piles of scattered papers are illuminated by the nearby monitors flashing CYPHER’s logo; one you are all too familiar with. Drat! You resolve to use your funds more carefully next time. You deploy your PULSE tracer drone to scan the room for possible travel routes recently opened up. It quickly feeds a list to your heads-up display. You quickly recognize one – the World Financial Institution -- that fits the pattern of CYPHER’s previous hits.”
- “Briefly, you inform your employer about your progress. Your success in anticipating CYPHER’s movement patterns seems to feed their desperation to catch the thief, as they quickly wire you some additional funds to ensure the criminal is caught. Perhaps your luck is turning around – these credits will let you continue traveling through PULSE instead of using the slow, outdated Geopositional Relocator System. You pocket the credits, share a brief word of appreciation to your benefactor, and continue with your work.”
- “You know of two routes to get to the World Financial Institution. Select one quickly, and you might just beat CYPHER to the punch next time.”

Failure First Trial – Run out of time:

- “The feeling in your gut direly notifies you that CYPHER is likely to get away if you don’t speed up your movement. Your mind fires a million decisions a second as you twist, jump, and collapse the remaining legs of your trip into one blur of movement through PULSE. It may have taken longer than you had hoped, but you reach your destination regardless in a feat of true aethereal mastery."

- "The clock's relentless ticking becomes more and more toiling on you and your work. Focusing your will into the system, you manage to get it to bypass a few checks to ensure you get to your destination before it's too late. Whew! You'll be paying for that tomorrow with a few heavy fines you couldn't afford…but those problems will be a drop in bucket if you manage to get the reward money for catching CYPHER."
- "You manifest back into the world from PULSE. Your mind goes fuzzy with the overload of physical sensations that comes with your body's cells realigning back into physical space. Once the screaming of your nerves and the ringing in your ears silences, you scope out your surroundings. Empty caches and piles of scattered papers are illuminated by the nearby monitors flashing CYPHER's logo; one you are all too familiar with. Drat! You resolve to work more quickly next time. You deploy your PULSE tracer drone to scan the room for possible travel routes recently opened up. It quickly feeds a list to your heads-up display. You quickly recognize one – the World Financial Institution -- that fits the pattern of CYPHER's previous hits."
- "Briefly, you inform your employer about your progress. Your success in anticipating CYPHER's movement patterns seems to feed their desperation to catch the thief, as they quickly wire you some additional funds to ensure the criminal is caught. You pocket the credits, share a brief word of appreciation to your benefactor, and continue with your work post-haste."
- "You know of two routes to get to the World Financial Institution. Select one quickly, and you might just beat CYPHER to the punch next time."

Failure Second Trial/Overall Session – time and/or money

- "Swimming slivers of the World Financial Institution slowly align into your vision and you emerge from your portal. You hardly have a moment to acclimate yourself before you smell the familiar acrid fumes of a new portal opening. With a subtle crackle of atoms and wisp of ozone, a glowing portal opens. You recognize the visage of CYPHER as he looks back at you from the portal's light, his newest heist's spoils glinting in his hands. Before you can react, he throws a small mechanism on the ground and jumps into the portal. The device beeps quickly and a burst of energy radiates throughout the area, killing all cybernetic devices. Your Cryptex sputters from the EMP, effectively preventing you from creating portals and cutting you off from pursuing your target. You curse your poor luck and start walking back to the nearest functioning communicator to relay the bad news to your employer. You're certain you'll be able to catch CYPHER with a little more work (and your spare Cryptex back at the office). Thank you for playing."

Success – Session End

- “You slide through the PULSE with the utmost of ease and emerge from the portal in front of the World Financial Institution – the next target on CYPHER’s latest crime spree. You hardly have a moment to acclimate yourself before you smell the familiar acrid fumes of a new portal opening …With a subtle crackle of atoms and wisp of ozone, CYPHER emerges in front of you, looking harried and nervous. You lock eyes immediately and time stops.”
- “You see beads of sweat running down CYPHER’s temples as you deliver a series of quick reflexive palm strikes, breaking his PULSE portal generator and downing the villain instantly, giving you the moment you need to handcuff him.”
- “You send a call to the authorities and your employer notifying them of your achievement.”
- “Congratulations! You’ve saved the world and, more importantly, managed to scrounge up enough credits to pay for the abysmally increasing rent you keep getting hit with every month.”
- “Thank you for playing.”
- [Experiment conducted in-person] “Please let the proctor know you have completed the task. You will now complete a few questions about your experience.”
- [Mturk version] “You will now complete a few questions about your experience. Once you have answered these questions, you’ve finished all tasks required.”

APPENDIX G

CYPHER PASSPHRASE AND KEY DEVELOPMENT

Cypher Encrypted passphrase development

Passphrase (cypher) and key generation by randomization. To create randomized pass phrases, an online random string generator was used (Randomness and Integrity Services Ltd., 2019). Duplicate and adjacent letters were allowed. Phrases were ranked in order of difficultly (0 = most difficult, 4 = easiest) based on the phrase length (character count [3,15]) and the number of matched alpha-numeric pairs. A matched pair occurred if the letter, assigned to the same key integer, appeared twice in the passphrase. It is theorized that matched pairs should be more quickly recognized from a deciphered string character, making the alpha-numeric table unnecessary. This reduces effort and time to solve the phrase, as well as possibly reducing the in-game currency wasted on incorrect entries. The following provides the detailed process for producing the encrypted passphrases in this project. The solutions for the encrypted passphrases were produced with an Excel formula and python code.

Randomizer Input Parameters.

Group 1: alpha only, length = 15 characters, n = 75 uniquely randomized strings.
Group 2: alpha only, length = 13 characters, n = 75 uniquely randomized strings.
Group 3: alpha only, length = 11 characters, n = 75 uniquely randomized strings.
Group 4: alpha only, length = 9 characters, n = 75 uniquely randomized strings.
Group 5: alpha only, length = 7 characters, n = 75 uniquely randomized strings.
Group 6: alpha only, length = 5 characters, n = 75 uniquely randomized strings.
Group 7: alpha only, length = 3 characters, n = 75 uniquely randomized strings.

- Example character strings.

15 Character Strings
LFIXUXWGVMCPNII

13 Character Strings

AEQVYHDONJBLS

11 Character Strings
CUFCSAVYNON

9 Character Strings
MBDRLDKMF

7 Character Strings
NRPZKTY

5 Character Strings
XBWVB

3 Character Strings
LCH

Matched Pairs Details and Examples. A matched pair occurs if the letter, assigned to the same key integer, appears twice in the passphrase. String Lengths: (15), (13), (11), (9), (7), (5), (3) x 60 each = 420 total unique strings.

15 Character String

Zero Match
Y C V L I H D S W V U N H E S
4 2 7 4 2 7 4 2 7 4 2 7 4 2 7

One Match
L F **I** X U X W G V M C P N I **I**
4 2 **7** 4 2 7 4 2 7 4 2 7 4 2 **7**

Two Match
A D R W **V** H **R** U L L I K **R** **V** V
4 2 7 4 **2** 7 **4** 2 7 4 2 7 **4** **2** 7

Three Match

H N N G **T** **V** **H** **T** Q N K **V** U Y K

4 2 7 4 **2** **7** **4** **2** 7 4 2 **7** 4 2 7

Four Match

W D **P** **X** **A** G **K** R Y **K** **A** R **X** M **P**

4 2 **7** **4** **2** 7 **4** 2 7 **4** **2** 7 **4** 2 **7**

Key Sequence Generation. Integers used for each key sequence (3 integers) were created using a random integer set generator (Randomness and Integrity Services Ltd., 2019).
The parameters used to create the sequences: 60 sets with 3 unique random, unsorted integers in each, taken from the [3, 20] range. These sets of three integers are sorted into Simple (lower numbers, (<10) and Hard (higher numbers, (≤10≤). Higher numbers are more difficult because of the increased the mental effort required to solve the encrypted cyphers.

- Example Key Sequences.
    - Hard Set: 12, 20, 11
    - Simple Set: 4, 3, 7

About the online randomization tool

From random.org:

> "Most random numbers used in computer programs are *pseudo-random*, which means they are generated in a predictable fashion using a mathematical formula. This is fine for many purposes, but it may not be random in the way you expect if you're used to dice rolls and lottery drawings.
> RANDOM.ORG offers *true* random numbers to anyone on the Internet. The randomness comes from atmospheric noise, which for many purposes is better than the pseudo-random number algorithms typically used in computer programs. People use RANDOM.ORG for holding drawings, lotteries and sweepstakes, to drive online games, for scientific applications and for art and music. The service has existed since 1998 and was built by Dr Mads Haahr of the School of Computer Science and Statistics at Trinity College, Dublin in Ireland. Today, RANDOM.ORG is operated by Randomness and Integrity Services Ltd."
> (Randomness and Integrity Services Ltd., 2019)

APPENDIX H

LIST OF RECORDED METRICS

CYPHER, All Recorded Metrics

Code length (categorical)
Key difficulty – e.g., Simple, Hard (categorical)
Server Choice (categorical, 2 levels)
In-game currency (continuous)
Time (continuous)
Switch count, yes/no (binomial)
Switch interval, early/late (binomial)
Mistakes input count (continuous)
Correct input count (continuous)
Completed cyphers (continuous, but negatively skewed because most will complete)
Time spent solving each cypher
Time spent reading prompts/choosing portal switch
Demographics information
Occupation (categorical, nominal)
Highest degree completed (categorical)
Age (continuous)
Gender (categorical)
Task Questions (categorical, nominal)
Chance Questions (binary)
Inter-trial Survey (categorical, nominal)
IUS-short (single score, continuous)

APPENDIX I

IRB DOCUMENTS

Instructions and Notes: • Depending on the nature of what you are doing, some sections may • not be applicable to your research. If so, mark as "NA". • When you write a protocol, keep an electronic copy. • You will need a copy if it is necessary to make changes.
1 Protocol Title Include the full protocol title: **Decision making in cybersecurity**
2 **Background and Objectives** Provide the scientific or scholarly background for, rationale for, and significance of the research based on the existing literature and how will it add to existing knowledge. • Describe the purpose of the study. • Describe any relevant preliminary data or case studies. • Describe any past studies that are in conjunction to this study.

Background and Justification:
Advancing defensive methodology against the growing threat of global cyber crime is a necessary and important area of research. Increasing defensive capabilities through cyber provision of misinformation shows great promise [7]. Specifically this refers to "the provision of misinformation that is realistic enough to confuse situational awareness and to influence and misdirect perceptions and decision processes" [3]. It is not enough to merely detect and guard against cyber warfare, a more dynamically adaptive approach to bolster offensive security must be taken [4]. In other words, mounting an effective counter attack including the human-in-the loop is a critical component in understanding how to protect networks because after all, attackers are human [8].

Previous research investigated the effects of cyber misinformation on attacker performance [3]. The authors presented a robust experimental design with preliminary results that deepen current understanding about attacker characteristics and task performance. Building upon this work, subsequent research investigated the effects of misinformation on cognitive bias in decision- making. In this context, cognitive bias is clearly defined and differentiated from other types of bias in that it refers specifically to human bias in decision- making that results in less than ideal outcomes [9].

Cyber misinformation traditionally may involve a decoy or honeypot system device. Such devices appear to be real, so an attacker focuses time and energy to infiltrate [1]. This allows a defender to block the intrusion and protect the network. Decoy systems are designed to look and act like real systems. For example, in a honeynet, phony assets are designed on a separate dummy network. The dummy network lures an attacker away from the real network by presenting assets that appear to be legitimate. The real network is thus obscured and protected. The decoy system can be integrated with an intrusion detection system that monitors and flags suspicious incoming activity. Once malicious activity is detected, the attacker is silently redirected to the phony network.

Although modern cyber security has advanced much past the early days, expert hackers often outwit some of the best defensive technology. For example, if the intrusion detection system (IDS) does not detect malicious activity, the attacker can pass through the network security under the guise of a normal user. Furthermore, IDS alerts are not always accurate. A defender can be overwhelmed and distracted by false alerts or fail to pay much attention to them at all. In addition, the lack of defenders available to respond to real incidents contributes to ineffective network security. Weak defenses are particularly problematic in network environments that are static. Once an attacker maps a network, a large-scale attack can be planned and executed. The use of misinformation in the form of a decoy supports higher confidence in an alert because only an attacker would attempt to access a phone machine.

In order to develop dynamic, adaptive systems, researchers are using artificial intelligence models to simulate cyber wargame scenarios [1, 8]. Drawing upon Game Theory and machine learning to balance defenders' advantage, work on modeling and simulation for artificial intelligence in adaptive defense systems is showing promise. Along with this research, in order to adequately develop AI capable of deceiving a human attacker, it is critical to evaluate these models with human subjects research. It is one thing to model a logical, binary situation according to a small set of rules. However, humans do not always operate in a rational manner. In order to understand how to model commonly displayed irrational decision-making, human subjects research is key. Investigating cognitive bias as a deceptive practice in defensive operations stands to inform future AI development [2]. To define and evaluate the large array of cognitive biases is beyond the scope of this research. Instead, we specifically focus on investigating *sunk cost fallacy* as a robust example of irrationality. The sunk cost fallacy has been well researched (see section 4) and presents a clear picture of poor decision-making in which one essentially "doubles down" on a bad hand.

Previous research has established the effects of misinformation on attackers' decision making [6]. The authors conducted further work focused on three traditional cognitive biases; confirmation bias, anchoring, and take-the-best heuristic; [5]. They found examples where decisions and goals were influenced by cyber misinformation and the attackers' cognitive biases that created less-than-ideal results (e.g. increased risk of detection, delayed forward progress toward exfiltration). Sunk cost fallacy was presented as another important bias for future work.

Building upon this research, the current project intends to take a deeper dive to evaluate the effects of misinformation to induce cognitive bias in cyber attackers.

3 Data Use

Describe how the data will be used. Examples include:

- Dissertation, Thesis, Undergraduate honors project
- Publication/journal article, conferences/presentations
- Results released to agency or organization
- Results released to participants/parents
- Results released to employer or school
- Other (describe)

These data collected from this study will be used in a PhD dissertation, in publication/journal articles, at conferences/presentations, and released to the affiliated agencies in the U.S. Department of Defense according to the release agreement with the sponsoring agency. The following indication is also present in the consent form per sponsor request and contract requirement: "Sponsorship: This research is being sponsored by the U.S. Department of Defense. DoD representatives are authorized to review anonymized research records."

4	**Inclusion and Exclusion Criteria** Describe the criteria that define who will be included or excluded in your final study sample. If you are conducting data analysis only describe what is included in the dataset you propose to use. Indicate specifically whether you will target or exclude each of the following special populations: • Minors (individuals who are under the age of 18) • Adults who are unable to consent • Pregnant women • Prisoners • Native Americans • Undocumented individuals

Participants will be recruited from online populations via internet postings to Mechanical Turk. Special populations will be excluded in total. Additional exclusions: participants who have completed this study previously.

Inclusion criteria: Participants will need to be fluent in speaking and reading the English language, understand how to use basic computer devices (keyboard and mouse), have normal or corrected-to-normal vision (self-reported), be over the age of 18, and be able to sit in front of a computer monitor for the full-length of the study.

Participants from Amazon Mechanical Turk will be limited to MTurkers who have participated in > 50 tasks and maintained a >95% Human Intelligence Task (HIT) approval rating to collect reliable data (e.g., Paolacci & Chandler, 2014). Recruitment from MTurk will also be limited by location to the United States at this time.

5	**Number of Participants** Indicate the total number of participants to be recruited and enrolled: 2200 participants are expected throughout the run of this experiment to achieve adequate power for all analyses. The number is high as we expect to run multiple variants (explained in the methods sections) each which need proper statistical power. It also takes into account the relatively higher rate of online-subject error rates, which raise the chance of data collected being below thresholds for examination

6	**Recruitment Methods** • Describe who will be doing the recruitment of participants. • Describe when, where, and how potential participants will be identified and recruited. • Describe and attach materials that will be used to recruit participants (attach documents or recruitment script with the application).

Only the researchers listed on the IRB protocol (trained ASU faculty and students, and DOD collaborators) will be involved in the recruitment of participants.

Participants may be recruited through a subject pool using SONA recruitment associated with the HumaNSystems Engineering 101, and Psychology 101 courses at ASU. Available studies are listed online via SONA with a brief description and interested students can sign up to participate. Participants from these pools will receive course credit in accordance with subject pool policies (i.e. the current study will award 1 credit for each hour of participation and in .5 increments, up to two total hours (2)). A brief description can be found in the recruitment documentation (Attached document "Recruitment – Credit")

Participants may also be recruited through personal networks, email lists, and other avenues in which they are familiar with the norms of solicitation in the group, or have received advanced permission from managers of those groups. A combination of online and physical flyers listing a short description of the study and recruitment criteria may also be posted in publicly accessible locations, such as campus bulletin boards, Craig's list, and community centers. These postings may also make use of various online experiment delivery systems, including Amazon's Mechanical Turk platform which automatically handles the recruitment and inclusion procedures. Importantly, data will be collected and stored on ASU-owned equipment, or ASU accounts and protected accordingly. Prospective participants will be asked to contact the researchers and confirm that they meet the study criteria before scheduling will take place. These participants will also be screened for whether they have participated in this specific experiment before. If they have, they will be excluded from participation.

7 Procedures Involved

Describe all research procedures being performed, who will facilitate the procedures, and when they will be performed. Describe procedures including:

- The duration of time participants will spend in each research activity.
- The period or span of time for the collection of data, and any long term follow up.
- Surveys or questionnaires that will be administered (Attach all surveys, interview questions, scripts, data collection forms, and instructions for participants to the online application).
- Interventions and sessions (Attach supplemental materials to the online application).
- Lab procedures and tests and related instructions to participants.
- Video or audio recordings of participants.
- Previously collected data sets that that will be analyzed and identify the data source (Attach data use agreement(s) to the online application).

Recruitment: as described above. Following inclusion criteria being met, participants given information on how to access the online version of the study).
Study duration: 1-2 hours (varies based on version; consent documents are provided to cover 1hour, 1.5 hours, and 2hours conditions)
Data collection time span: June 2020 – December 2021, no long term follow up is necessary.
Procedure & Instructions: The participant will be asked to solve puzzles to break the passwords and achieve the goal of gaining access to a data server while chasing a fictional character (See Attachment A). No real systems are involved. Participants will be given initial instructions. Participants begin with a trial walkthrough along with a brief explanation and motivational section with a storyline (Attachment A) and proceed to the experiment only when they have shown they can correctly solve the puzzle.

Moving to the experimental sessions, participants again are given cyphers to solve. Feedback is given on each entry. Our key variable of analysis is whether, during the partial solution of these cyphers, if offered a chance to "switch" to a new set of cyphers, whether they will select to do so, or rather to continue on solving in their current server/portal. Therefore, before the full solution is achieved but upon solving a set number of the initial characters of the ciphertext, participants will receive a notification on their screen and given some information about a new set of cyphers, and their lengths. Participants are then asked to make a choice whether to stay in their current set, or switch to a new set.

Experiment will vary, separately and occasionally simultaneously, a number of important variables related to conditions of whether a participant may choose to switch or stay on their tasks. These are:
* when the new server is presented to them (based on # of solved characters in the first password). We may vary to any location within a cypher as to when the option is presented.
* what the new server's expected password length is. We may vary both the length specified, and the certainty of the information itself - whether it is a range of values, or a specific value.
* the number of characters in the cyphers being solved in general. We may vary these to be very long (10+ characters) or very short (5 or fewer).
* the difficulty of the key used to solve them (we may vary the difficulty of using the key in the solution based on number of transfers and mental addition challenge)
* the number of cyphers being solved (we may vary these again based in part on time for the experiment allotted, and general length of cyphers used)
* the amount of time given to participants to solve cyphers
* the amount of resources in the game available to solve cyphers, and the relative cost of entry/incorrect entry
* whether our current background storyline (Attachment A) is used or not following the training phase

* whether participants are asked the following questions either after making these switch selections, or at the end of the study:
- "Why did you choose to [switch] or [stay]?"
- "How difficult were these cyphers to solve, on a scale from 1 to 10, with 10 being extremely hard, and 1 being extremely easy?"
- "Rate your enjoyment in the cypher task on a scale from 1 to 10, with 10 being extremely enjoyable, and 1 being extremely not enjoyable"

All will always be measuring participants choice to either: (1) stay on the current task and finish the decipher, or (2) switch to the new code and begin deciphering those passwords, as well as (3) response times, (4) resources used and remaining, time used and remaining, and (5) total number of passwords and characters in cyphers that have been solved.

Participants will have enough time to solve cyphers given to them, even if they always choose the longest codes available, within the limits of the experiment. The intent is to create a quantifiable 'cost' for each decipher action taken, and examine the sunk cost fallacy in the context of task selection in cybersecurity.

Following the cypher game, participants will be asked a series of demographic (Attachment B), task (Attachment C), and survey questions (D; Intolerance of Uncertainty Scale (Short), Carleton, Norton, & Asmundson, 2007). All data will be recorded using an anonymous participant ID. Data will be stored in a locked cabinet in the laboratory, or on a secured computer.

8 Compensation or Credit

- **Describe the amount and timing of any compensation or credit to participants.**
- **Identify the source of the funds to compensate participants**
- **Justify that the amount given to participants is reasonable.**
- **If participants are receiving course credit for participating in research, alternative assignments need to be put in place to avoid coercion.**

We will be recruiting participants from other sources using incentive of paid compensation. In these cases we will compensate participants $4-8 for their time (at $4/hr). This is the result of using a service like Amazon Mturk. The funding source for this compensation comes from the grant listed in the application to ASU, "Oppositional Human Factors" (GR37294), funds manager Tanya Dalton (tanya.dalton@asu.edu), PI: Robert Gutzwiller (rgutzwil@asu.edu)

9 Risk to Participants

List the reasonably foreseeable risks, discomforts, or inconveniences related to participation in the research. Consider physical, psychological, social, legal, and economic risks.

There are no foreseeable risks to participants.

10 Potential Benefits to Participants Realistically describe the potential benefits that individual participants may experience from taking part in the research. Indicate if there is no direct benefit. Do **not** include benefits to society or others.
There is no direct benefit to participants, other than they may benefit from learning about cybersecurity terminology. Notably they do not learn any real-world hacking skill or tool. They may also learn about human subjects experimentation methods by experiencing them directly.

11 Privacy and Confidentiality Describe the steps that will be taken to protect subjects' privacy interests. "Privacy interest" refers to a person's desire to place limits on with whom they interact or to whom they provide personal information. Click here for additional guidance on ASU Data Storage Guidelines. Describe the following measures to ensure the confidentiality of data: • Who will have access to the data? • Where and how data will be stored (e.g., ASU secure server, ASU cloud storage, filing cabinets, etc.)? • How long the data will be stored? • Describe the steps that will be taken to secure the data during storage, use, and transmission. (e.g., training, authorization of access, password protection, encryption, physical controls, certificates of confidentiality, and separation of identifiers and data, etc.). • If applicable, how will audio or video recordings will be managed and secured. Add the duration of time these recordings will be kept. • If applicable, how will the consent, assent, and/or parental permission forms be secured. These forms should separate from the rest of the study data. Add the duration of time these forms will be kept. • If applicable, describe how data will be linked or tracked (e.g. masterlist, contact list, reproducible participant ID, randomized ID, etc.). If your study has previously collected data sets, describe who will be responsible for data security and monitoring.
Data will be collected anonymously. Each participant's data will be labeled only with an ID code that is never linked to their name or personally-identified data. Data will be stored on secure University network resources and accounts. The data will be stored approximately 10 years. Only the PI and collaborators listed will have access to the data. Data storage and PCs/laptops used to collect or analyze the data will be password protected.

12 Consent Process

Describe the process and procedures process you will use to obtain consent. Include a description of:

- Who will be responsible for consenting participants?
- Where will the consent process take place?
- How will consent be obtained?
- If participants who do not speak English will be enrolled, describe the process to ensure that the oral and/or written information provided to those participants will be in that language. Indicate the language that will be used by those obtaining consent. Translated consent forms should be submitted after the English is approved.

The PI or collaborator listed above will be responsible for conducting the consent process. The consent process ~~will take place in an on-campus ASU research lab at the Polytechnic Campus, Simulator Building, Rooms 254, 256, 237C, or 240, or at the ASU Tempe Campus, Interdisciplinary Science & Technology Building IV, Room 432, or the process~~ will take place online for online studies administered virtually as described in recruitment.

COVID-19 Restriction plan:

- Any in-person research will not begin until after the COVID-19 related suspension has been lifted. Additionally, the protocol will follow the most current recommendations given by ASU and the CDC for any in-person studies.

An information sheet will describe the study, confidentiality, voluntary participation, and compensation. Participants will read this document and then communicate their clear verbal ~~(in person) or~~ online (click I agree button) consent to participate before beginning the study.

Participants who do not speak English, or are under 18, or do not have normal or corrected-to-normal vision will not be enrolled in the study. We also will not enroll those potential participants who indicate they have previously completed this study.

We also have added the required statement "include the following statement: Sponsorship: This research is being sponsored by the U.S. Department of Defense. DoD representatives are authorized to review anonymized research records." To all consent documents.

The funder will be notified of any changes to the study.

13 Training

Provide the date(s) the members of the research team have completed the CITI training for human participants. This training must be taken within the last 4 years. Additional information can be found at: Training.

Research Personnel (updated 04/2020 in this mod, attached certificates)
Robert Gutzwiller, PhD (PI) – Citi Training dates 22, 23-Mar-2018
Chelsea Johnson (ASU HSE graduate student) – Citi Training dates: 28-Aug-2019
Andrew Rogers (DOD collaborator) – Citi Training dates: 24-Oct-2018
Temmie Shade (DOD collaborator) – Citi Training dates: 07-Aug-2019
Kim Ferguson-Walter (DOD collaborator) – Citi Training dates: 30-Mar-2020
Rick VanTassel (DOD collaborator) – Citi Training dates:
Elizabeth Niedbala (DOD collaborator) - Citi Training dates:

References:

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[2] K. Ferguson-Walter, D. LaFon, and T. Shade, "Friend or Faux: Deception for Cyber Defense", *Journal of Information Warfare*, *16*(2), 2017, pp. 28–42.

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EXEMPTION
GRANTED

Robert Gutzwiller
IAFSE-PS: Human Systems Engineering (HSE)
-
Robert.Gutzwiller@asu.edu

Dear Robert Gutzwiller:

On 5/17/2021 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Attack Surface: Decision-making in an abstracted cyber environment
Investigator:	Robert Gutzwiller
IRB ID:	STUDY00013811
Funding:	Name: NSA: Central Security Service (CSS), Grant Office ID: FP00021315, Funding Source ID: H98230- 19-C-0605
Grant Title:	FP00021315;
Grant ID:	FP00021315;
Documents Reviewed:	• Appendix A -- AS_Experiment Instructions.pdf, Category: Participant materials (specific directions for them); • Appendix B -- AS_Inter-Trial Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Appendix C -- AS_Post-Session Survey.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Appendix D -- AS_notification and questions.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Appendix E -- AS_Comprehension

	Check Items, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Attack Surface Recruitment Script - 1 hour.pdf, Category: Recruitment Materials;

	• Attack Surface Recruitment Script - 1 hour.pdf, Category: Recruitment Materials; • Attack Surface Recruitment Script - 1.5 hour.pdf, Category: Recruitment Materials; • Attack Surface Recruitment Script - 1.5 hour.pdf, Category: Recruitment Materials; • Attack Surface Recruitment Script - 2 hour.pdf, Category: Recruitment Materials; • Attack Surface Recruitment Script - 2 hour.pdf, Category: Recruitment Materials; • Attack Surface_Consent -- 1 hour.pdf, Category: Consent Form; • Attack Surface_Consent -- 1.5 hour.pdf, Category: Consent Form; • Attack Surface_Consent -- 2 hour.pdf, Category: Consent Form; • Consent - 1 hour, Category: Consent Form; • Consent - 1.5 hour, Category: Consent Form; • Consent - 2 hour, Category: Consent Form; • FP21315 - SOW.pdf, Category: Sponsor Attachment; • Protocol_Attack_Surface, Category: IRB Protocol;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 Exempt (2)(i) Tests, surveys, interviews, or observation, and Exempt (3)(i)(A) Benign behavioral interventions on 5/17/2021.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

If any changes are made to the study, the IRB must be notified at research.integrity@asu.edu to determine if additional reviews/approvals are required. Changes may include but not limited to revisions to data collection, survey and/or interview questions, and vulnerable populations, etc.

Sincerely,

IRB Administrator

cc: Chelsea Johnson
Hansol
Rheem
Chelsea
Johnson
Christina
Lewis

APPENDIX J

EXPLORATORY ANALYSES

Exploratory Analysis

Experiment 1, Trial 1 Results by Condition and DV

Comparing those who switched portals with those who did not, across all four conditions, we can see some significant differences in behavior in utilized resources - time elapsed and coins spent.

In this section, we analyze time elapsed resources used in two meaningful intervals in each trial; (1) the interval that includes time from the start of the trial until the decision was made to stay on the current portal and cypher, or switch to a new portal and cypher and second, (2) the total time to complete the trial.

TIME ANALYSES
MANOVA, Bonferroni – H4
Main Effects and Interactions

In Cypher experiment 1, to complete the task, the Early condition required less resources as follows: (1) time spent from the start of the trial until the decision was made to stay on the current portal and cypher, or switch to a new portal, and (2) coins utilized. Thus, for the time until switch and coin analyses, the Early conditions were split from the Late conditions. All conditions are compared on the total time to complete the trial.

A one-way multivariate analysis of variance was conducted on the influence of an independent variable (condition + switch decision) on (1) the time spent until the decision was made to stay on the current portal and cypher, or switch to a new portal and cypher and (2) the total time to complete the trial. In Cypher experiment 1, the conditions of Early and Late required a distinctly different level of resources to complete the task. Thus, for these analyses, the Early conditions were split from the Late conditions.

Each condition was combined with the switch decision because switching was a binomial, dependent variable more appropriately analyzed with a Chi^2 analysis. The independent variable included the two conditions, split between the did NOT switch or did outcome for a total of 4 levels . Effects were statistically significant at the .05 significance level.

Early Conditions
Time: Start of trial until Switch
The analysis showed a significant difference in the main effect of condition on the time spent until the decision was made to stay or switch, $F(3, 180) = 3.37$, $p = .02$, Pillai's Trace = 0.39, partial $eta^2 = 0.195$, and the total time spent to complete trial 2, $F(3, 180) = 6.28$, $p < .001$, Pillai's Trace = 0.39, partial $eta^2 = 0.096$.

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent prior to the switch opportunity was*** significantly different in the following cases:

Participants in the Early-Uncertain condition (EU0, *M* = 70.91) who did NOT switch spent significantly less time prior to the switch opportunity than those in the Early-Uncertain condition who switched (EU1, *M* = 84.54, *p* = .03).

Interpretation.

All parameters being equal prior to the certain or uncertain switch message, we did not expect to find a significant difference between those who ultimately chose to switch compared to those who did not. We can speculate that those who chose to switch may have done so due to an emotional response (e.g., frustration) or as a means of reducing cognitive load, or effort aversion. Results for the open-ended survey analyses, discussed later, will help us to understand these behaviors.

Early Conditions
Time: Trial Completion

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent to complete trial 1*** significantly different in the following cases:

Participants in the Early-Uncertain condition (EU1, *M* = 263.90) who switched spent significantly less time to complete trial 2 than those in the Early-Uncertain condition who did not (EU0, *M* = 335.65, *p* = .001). Participants in the Early-Uncertain condition (EU1, *M* = 263.90) who switched spent significantly less time to complete trial 2 than those in the Early-Certain condition (EC0, *M* = 331.88, *p* = .002) who did NOT switch.

Interpretation.

These results align with the experimental design in that switching portals saved time because the cyphers in the switch portal were shorter.

Late Conditions

Utilized Resource: Time				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Late-Certain, did NOT switch	**LC0**	50	91.20	307.74
Late-Certain, switched	**LC1**	32	81.84	237.25
Late-Uncertain, did NOT switch	**LU0**	42	105.88	370.26

Late-Uncertain, switched	**LU1**	46	107.00	305.48
	Total	170		

Late Conditions
Time: Start of trial until Switch

The analysis showed a significant difference in the main effect of condition on the time spent until the decision was made to stay or switch, $F(3, 169) = 10.71$, $p < .001$, Pillai's Trace = 0.37, partial $eta^2 = 0.161$, and the total time spent to complete trial 2, $F(3, 169) = 18.09$, $p < .001$, Pillai's Trace = 0.37, partial $eta^2 = 0.096$.

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent prior to the switch*** opportunity was significantly different in the following cases:

Participants in the Late-Uncertain condition who did NOT switch, (LU0, $M = 105.88$ spent significantly more time until the decision was made to stay or switch than those in the Late-Certain conditions who did NOT switch (LC0, $M = 91.20$) and than those who did (LC1, $M = 81.84$). Participants in the Late-Uncertain condition who switched (LU1, $M = 107.00$) spent significantly more time until the decision was made to stay or switch than those in the Late-Certain conditions who did NOT switch (LC0, $M = 91.20$) and than those in the Late-Certain who switched (LC1, $M = 81.84$).

Late Conditions
Time: Trial Completion

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent to complete trial 2*** was significantly different in the following cases:

Participants in the Late-Uncertain condition who did NOT switch (LC0, $M = 307.74$) spent significantly more time to complete trial 2 than those in the (LC1, $M = 237.25$). Participants in the Late-Certain condition who switched (LC1, $M = 237.25$) spent significantly less time to complete trial 2 than those in the Late-Uncertain condition who did NOT switch (LU0, $M =370.26$). Participants in the Late-Uncertain condition who did NOT (LU0, $M = 370.26$) switch spent significantly more time than those in the Late-Uncertain condition who switched (LU1, $M = 305.48$), and than those in the Late-Certain condition who did NOT switch (LC0, $M = 307.74$). Finally, participants in the Late-Uncertain condition who switched (LU1, $M = 305.48$) spent significantly more time than those in the Late-Certain condition who switched (LC1, $M = 237.25$).

COIN ANALYSES
Kruskal-Wallis H – H4
Main Effects and Interactions
EUEC – Coins
LULC – Coins

Analysis 1: Early-Uncertain, Early-Certain

In the Cypher experiment 1, to complete the task, the conditions of Early and Late required a different level of resources. Thus, for coin analyses, the Early conditions were split from the Late conditions and between the switched or did not outcome for a total of 8 levels (see Table x). Effects were statistically significant if they exceeded the .05 criterion level.

Utilized Resource: Coins				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Early-Certain, did NOT switch	**EC0**	44	7.57	57.32
Early-Certain, switched	**EC1**	41	7.63	45.51
Early-Uncertain, did NOT switch	**EU0**	44	7.55	58.55
Early-Uncertain, switched	**EU1**	46	7.59	44.48
	Total	**175**		

Utilized Resource: Coins				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Late-Certain, did NOT switch	**LC0**	49	14.06	58.82
Late-Certain, switched	**LC1**	34	13.88	50.71
Late-Uncertain, did NOT switch	**LU0**	53	14.11	59.51
Late-Uncertain, switched	**LU1**	34	14.68	52.47
	Total	**170**		

Experiment 1, Trial 2 Results by Condition and DV

The main effects of the Certain versus Uncertain conditions were significant; therefore, we next analyze participants' resource use (time and coins.) See Appendix xx for all exploratory analyses and results in which the main effect of switching was not significant.

TIME ANALYSES

Utilized Resource: Time	

Condition Description	Condition Code	N	Until Switch Mean	Trial Completion Mean
Early-Certain, did NOT switch	**EC0**	52	72.60	331.88
Early-Certain, switched	**EC1**	36	77.61	314.00
Early-Uncertain, did NOT switch	**EU0**	43	70.91	335.65
Early-Uncertain, switched	**EU1**	50	84.54	263.90
	Total	181		

Early Conditions
Time: Start of trial until Switch
The analysis showed a significant difference in the main effect of condition on the time spent until the decision was made to stay or switch, $F(3, 180) = 3.37$, $p = .02$, Pillai's Trace = 0.39, partial eta^2 = 0.195, and the total time spent to complete trial 2, $F(3, 180) = 6.28$, $p < .001$, Pillai's Trace = 0.39, partial eta^2 = 0.096.

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent prior to the switch opportunity was*** significantly different in the following cases:

Participants in the Early-Uncertain condition (EU0, M = 70.91) who did NOT switch spent significantly less time prior to the switch opportunity than those in the Early-Uncertain condition who switched (EU1, M = 84.54, p = .03).

Interpretation.
All parameters being equal prior to the certain or uncertain switch message, we did not expect to find a significant difference between those who ultimately chose to switch compared to those who did not. We can speculate that those who chose to switch may have done so due to an emotional response (e.g., frustration) or as a means of reducing cognitive load, or effort aversion. Further research is required to better understand this result.

Early Conditions
Time: Trial Completion

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent to complete trial 1*** significantly different in the following cases:

Participants in the Early-Uncertain condition (EU1, M = 263.90) who switched spent significantly less time to complete trial 2 than those in the Early-Uncertain condition who did not (EU0, *M* = 335.65, *p* = .001). Participants in the Early-Uncertain condition (EU1, *M* = 263.90) who switched spent significantly less time to complete trial 2 than those in the Early-Certain condition (EC0, *M* = 331.88, *p* = .002) who did NOT switch.

Interpretation.

These results align with the experimental design in that switching portals saved time because the cyphers in the switch portal were shorter.

Late Conditions

Utilized Resource: Time					
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Late-Certain, did NOT switch	**LC0**	50	91.20	307.74
Late-Certain, switched	**LC1**	32	81.84	237.25
Late-Uncertain, did NOT switch	**LU0**	42	105.88	370.26
Late-Uncertain, switched	**LU1**	46	107.00	305.48
	Total	170		

Late Conditions
Time: Start of trial until Switch

The analysis showed a significant difference in the main effect of condition on the time spent until the decision was made to stay or switch, $F(3, 169) = 10.71$, $p < .001$, Pillai's Trace = 0.37, partial eta^2 = 0.161, and the total time spent to complete trial 2, $F(3, 169) = 18.09$, $p < .001$, Pillai's Trace = 0.37, partial eta^2 = 0.096.

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent prior to the switch*** opportunity was significantly different in the following cases:

Participants in the Late-Uncertain condition who did NOT switch, (LU0, *M* = 105.88 spent significantly more time until the decision was made to stay or switch than those in the Late-Certain conditions who did NOT switch (LC0, *M* = 91.20) and than those who did (LC1, *M* = 81.84). Participants in the Late-Uncertain condition who switched (LU1, *M* = 107.00) spent significantly more time until the decision was made to stay or switch than those in the Late-Certain conditions who did NOT switch (LC0, *M* = 91.20) and than those in the Late-Certain who switched (LC1, *M* = 81.84).

Late Conditions
Time: Trial Completion

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent to complete trial 2*** was significantly different in the following cases:

Participants in the Late-Uncertain condition who did NOT switch (LC0, *M* = 307.74) spent significantly more time to complete trial 2 than those in the (LC1, *M* = 237.25). Participants in the Late-Certain condition who switched (LC1, *M* = 237.25) spent significantly less time to complete trial 2 than those in the Late-Uncertain condition who did NOT switch (LU0, *M* =370.26). Participants in the Late-Uncertain condition who did NOT (LU0, *M* = 370.26) switch spent significantly more time than those in the Late-Uncertain condition who switched (LU1, *M* = 305.48), and than those in the Late-Certain condition who did NOT switch (LC0, *M* = 307.74). Finally, participants in the Late-Uncertain condition who switched (LU1, *M* = 305.48) spent significantly less time than those in the Late-Certain condition who switched (LC1, *M* = 237.25).

COIN ANALYSES

Statistical Analysis: Kruskal-Wallis H, Dunn's Test, Benjamini-Hochberg correction

The coins spent prior to the switch opportunity and total spent in each trial were not normally distributed (Shapiro-Wilk's test, $p < 0.001$). As such, the Kruskal-Wallis H test with Benjamini-Hochberg correction was used to analyze the data. All tests were asymptotic, and the significance level was set to .05.

A Kruskal-Wallis H with Dunn's Test and Benjamini Hochberg corrections was conducted on the influence of two variables (condition + switch decision) on (1) coins spent from the start of the trial until the decision was made to stay on the current portal and cypher, or switch to a new portal and cypher and (2) the total coins spent to complete a trial.

Early Conditions

Utilized Resource: Coins				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Early-Certain, did NOT switch	**EC0**	44	7.57	58.76
Early-Certain, switched	**EC1**	41	7.63	47.78
Early-Uncertain, did NOT switch	**EU0**	44	7.55	58.55
Early-Uncertain, switched	**EU1**	46	7.59	57.83
	Total	**175**		

Coins: Start of trial until Switch

A Kruskal-Wallis H test showed there is no statistically significant difference in coins spent to switch, $\chi^2(3, N = 178) = 3.93, p = 0.27$.

Coins: Trial Completion

However, the test showed a significant difference in the total coins spent to complete Trial 2, $\chi^2(3, N = 178) = 114.48, p = .03$

A Dunn's post hoc test with Benjamini-Hochberg correction for False Detection Rate (FDR) was conducted on the ***coins spent to complete Trial 2***. The total coins spent in the Early-Uncertain (EU1, $M = 57.83$) and Early-Certain (EC1, $M = 47.78$) who switched were less than Early-Certain (EC0, $M = 58.76$, FDR, $p = 0.04$) and Early-Uncertain conditions who did NOT switch (EU0, $M = 57.83$, FDR, $p = 0.04$).

Interpretation.
These results demonstrate that regardless of condition, participants who switched spent fewer coins compared to those who did not.

Late Conditions

Utilized Resource: Coins				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Late-Certain, did NOT switch	**LC0**	49	14.06	58.82
Late-Certain, switched	**LC1**	34	13.88	50.71
Late-Uncertain, did NOT switch	**LU0**	53	14.11	59.51
Late-Uncertain, switched	**LU1**	34	14.16	56.14
	Total	**170**		

The coins spent prior to the switch opportunity and total spent in Trial 2 were not normally distributed (Shapiro-Wilk's test, $p < 0.001$). As such, the Kruskal-Wallis H test with Benjamini-Hochberg correction was used to analyze the data. All tests were asymptotic, and the significance level was set to 0.05.

Coins: Start of trial until Switch

A Kruskal-Wallis H test showed there was no statistically significant difference in coins spent to switch, $\chi^2(3, N = 169) = 6.54, p = 0.08$.

Coins: Trial Completion

However, the test showed a significant difference in the total coins spent to complete Trial 2, $\chi^2(3, N = 175) = 101.32$, $p < 0.001$.

A Dunn's post hoc test with Benjamini-Hochberg correction for False Detection Rate (FDR) was conducted on the ***coins spent to complete Trial 2***.

Participants in the Late-Certain condition who switched (LC1, $M = 50.24$) spent less compared to those in the Late-Certain and Late-Uncertain conditions who do did NOT switch (LC0, $M = 58.76$, FDR, $p = 0.04$; LU0, $M = 59.28$, FDR, $p = 0.04$).

In addition, the total coins spent in the Late-Uncertain condition who switched (LU1, $M = 51.72$) were less those in the Late-Certain (LC0, $M = 58.76$, FDR, $p = 0.04$) and Late-Uncertain conditions (LU0, $M = 59.28$, FDR, $p = 0.04$) who did NOT switch. All others are non-significant.

Experiment 2, Trial 1 Results by Condition and DV

TIME ANALYSES
MANOVA, Bonferroni - H5
Main Effects and Interactions
Time

Hypothesis 5. The sunk cost fallacy occurs more in uncertain conditions when the project is more difficult.

Task difficulty and uncertainty cooperatively contribute to the decision to persist or withdraw from the task. Those in the Hard-Uncertain condition will switch less and spend more resources than those in the Hard-Certain, or Simple conditions.

Utilized Resource: Time				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**
Simple-Certain, did NOT switch	**SC0**	53	138.40	354.02
Simple-Certain, switched	**SC1**	34	150.94	343.41
Simple-Uncertain, did NOT switch	**SU0**	60	137.37	356.93
Simple-Uncertain, switched	**SU1**	35	131.77	303.89
Hard-Certain, did NOT switch	**HC0**	47	157.57	441.06
Hard-Certain, switched	**HC1**	36	152.36	343.47

Hard-Uncertain, did NOT switch	**HU0**	46	177.48	456.00
Hard-Uncertain, switched	**HU1**	30	160.83	368.40
Total		**341**		

Simple Conditions
Time: Start of trial until Switch
The analysis showed a significant difference in the main effect of condition on the time spent prior to the switch opportunity was significant, $F(7, 340) = 5.20$, $p < .001$, Pillai's Trace = 0.37, partial eta^2 = 0.19.

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent prior to the switch opportunity was*** significantly different in the following cases:

Participants in the Simple-Certain condition (SC0, $M = 138.40$) who did NOT switch spent significantly less time prior to the switch opportunity than those in the Hard-Uncertain condition who did not switch (HU0, $M = 177.48$, $p < .001$). Participants in the Hard-Uncertain condition who did not switch (HU0, $M = 177.48$) spent more time than those in the Simple-Uncertain condition who did not switch (M = 137.37, p < .001) and than those in the Simple-Uncertain condition who did switch (M = 131.77, p < .001),

Interpretation.
The Simple conditions required less time to complete the trial. These results suggest that the Simple conditions required less time investment

Interpretation.
All parameters being equal prior to the certain or uncertain switch message, we did not expect to find a significant difference between those who ultimately chose to switch compared to those who did not. We can speculate that those who chose to switch may have done so due to an emotional response (e.g., frustration) or as a means of reducing cognitive load, or effort aversion. Further research is required to better understand this result.

Simple Conditions
Time: Trial Completion
The total time to complete the trial was significant, $F(7, 340) = 14.50$, $p < .001$, Pillai's Trace = 0.37, partial eta^2 = 0.19,

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent to complete trial 1*** significantly different in the following cases:

Participants in the Hard-Certain condition who switched (HC1, *M* = 343.47) spent significantly less time to complete trial 1 than those in the Hard-Uncertain condition who did not (HU0, *M* = 456.00, $p < .001$). Participants in the Simple-Certain condition who did not switch (SC0, *M* = 354.02) spent significantly less time to complete trial 1 than those in the Hard-Certain condition (HC0, *M* = 441.06, $p = .002$) who did NOT switch and the Hard-Uncertain condition who did not switch, (HU0, M = 456.00, p < .001).

Participants in the Simple-Certain condition who switched spend significantly less time to complete trial 1 than the Hard-Certain Condition who did not switch (HC0, M = 441.06) and the Hard-Uncertain condition who did not switch (HU0, M = 456.00, p < .001). Participants in the Simple-Uncertain condition who did not switch (SU0, M = 356.93) spent significantly less time than those in the Hard-Certain condition who did not switch (HC0, M = 441.06, p < .001), and than those in the Hard-Uncertain condition who did not switch HU0, M = 456.00, p < .001). Participants in the Simple-Uncertain condition who switched (SU0, M = 356.93) spent significantly less time than those in the Hard-Certain condition who did not switch (HC0, M = 441.06, p < .001), and those in the Hard-Uncertain condition who did not switch (HU0, M = 456.00, p < .001.)

COIN ANALYSES

The coins spent prior to the switch opportunity and total spent in each trial were nonnormally distributed (Shapiro-Wilk's test, p < 0.001). As such, the Kruskal-Wallis H test with Benjamini-Hochberg correction was used to analyze the data. All tests were asymptotic and the significance level was set to 0.50.

A Kruskal-Wallis H test showed there was a statistically significant difference in coins spent to switch, $\chi^2(3, N = 342) = 15.20$, $p = 0.03$ and in the total coins spent to complete Trial 1
$\chi^2(3, N = 342) = 191.53$, $p = 0.00$.

A Dunn's post hoc test with Benjamini-Hochberg correction for False Detection Rate (FDR) was conducted on the coins spent to switch opportunity. Participants in the **Certain-Simple condition who switched** (SC1, *M* = 18.39) spent significantly less than those in the Uncertain-Hard condition who did NOT switch (HU0, *M* = 19.65, FDR, $p = 0.05$) and those in the Uncertain-Hard condition who switched (HU1*, M* = 20.16, FDR, $p = 0.02$).

Participants in the **Uncertain-Simple condition who did NOT switch** (SU0, *M* = 18.57) spent significantly less than those in the Uncertain-Hard condition who switched (HU1*, M* = 20.16, FDR, $p = 0.04$). Furthermore, participants in the Certain-Simple conditions who switched spent significantly less (SC1, *M* = 18.39) than those in the Uncertain-Hard condition who did NOT switch (HU0, *M* = 19.65, FDR, *p* = 0.05).

These results demonstrate two findings, (1) they align with the fact that the cyphers were shorter in the switch portal, hence fewer coins were spent compared to those in the starting portal, and (2) the certain-uncertain manipulation did not significantly affect decisions about coin resources.

A Dunn's post hoc test with Benjamini-Hochberg correction for False Detection Rate (FDR) was conducted on the total coins spent to complete Trial 1.

Participants in the **Uncertain-Simple condition who** switched (SU1*, M* = 54.88) spent significantly less than those in the Uncertain and Certain-Simple conditions who did NOT switch (SU0, *M* = 64.10, FDR, *p* = 0.02; SC0*, M* = 64.64, FDR, *p* = 0.02), those in the Uncertain and Certain-Hard conditions who did NOT switch (HU0, *M* = 66.35, FDR, *p* = 0.04; HC0, *M* = 65.12, FDR, *p* = 0.04;) and those in the Certain-Hard condition who switched (HC1*, M* = 57.89, FDR, *p* = 0.05).

Participants in the **Certain-Simple condition who switched** (SC1*, M* = 55.03) spent significantly less than those in the Uncertain and Certain-Simple conditions who did NOT switch (SU0, *M* = 64.10, FDR, *p* = 0.04; SC0*, M* = 64.64, FDR, *p* = 0.04), and than those in the Uncertain and Certain-Hard conditions who did NOT switch (HU0, *M* = 66.35, FDR, *p* = 0.04; HC0, *M* = 65.12, FDR, *p* = 0.04).

These results demonstrate two findings, (1) they align with the fact that the cyphers were shorter in the switch portal, hence fewer coins were spent compared to those in the starting portal, and (2) the certain-uncertain manipulation did not significantly affect decisions about coin resources.

Participants in the **Certain-Hard condition who switched** (HC1*, M* = 57.89) spent significantly less than those in the Uncertain and Certain-Simple conditions who did NOT switch (SU0, *M* = 64.10, FDR, *p* = 0.04; SC0*, M* = 64.64, FDR, *p* = 0.04), and than those in the Uncertain and Certain-Hard conditions who did NOT switch (HU0, *M* = 66.35, FDR, *p* = 0.04; HC0, *M* = 65.12, FDR, *p* = 0.04).

These results demonstrate two findings, (1) they align with the fact that the cyphers were shorter in the switch portal, hence fewer coins were spent compared to those in the starting portal, and (2) the certain-uncertain manipulation did not significantly affect decisions about coin resources.

Participants in the **Uncertain-Hard condition who switched** (HU1*, M* = 57.87) spent significantly less than those in the Uncertain and Certain-Simple conditions who did NOT switch (SU0, *M* = 64.10, FDR, *p* = 0.04; SC0*, M* = 64.64, FDR, *p* = 0.04), and than those in the Uncertain and Certain-Hard conditions who did NOT switch (HU0, *M* = 66.35, FDR, *p* = 0.04; HC0, *M* = 65.12, FDR, *p* = 0.04).

These results demonstrate two findings, (1) they align with the fact that the cyphers were shorter in the switch portal, hence fewer coins were spent compared to those in the starting portal, and (2) the certain-uncertain manipulation did not significantly affect decisions about coin resources.

Experiment 2, Trial 2 Results by Condition and DV

Time: Start of trial until Switch

Descriptive Statistics

	T2_cond_SW	Mean	Std. Deviation	N
T2_Time_Switch	HC0	137.72	32.708	47
	HC1	126.42	26.124	38
	SC0	100.48	24.519	46
	SC1	114.12	36.823	42
	HU0	143.29	35.019	45
	HU1	131.97	37.181	32
	SU0	101.15	30.002	54
	SU1	98.70	25.893	40
	Total	118.53	35.352	344
TTLtimeT2	HC0	390.02	87.848	47
	HC1	317.37	57.036	38
	SC0	306.52	70.388	46
	SC1	296.43	82.778	42
	HU0	402.31	83.375	45
	HU1	360.03	96.918	32
	SU0	298.65	80.789	54
	SU1	254.73	60.346	40
	Total	328.15	91.234	344

Time Analysis - MANOVA

The analysis showed a significant difference in the main effect of condition on the time spent until the decision was made to stay or switch, $F(7, 344) = 14.78$, $p < .001$, Pillai's Trace = 0.43, partial eta^2 = .24, and the total time spent to complete trial 2, $F(7, 344) = 18.39$, $p < .001$, Pillai's Trace = 0.37, partial eta^2 = 0.28.

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent prior to the switch*** opportunity was significantly different in the following cases:

Participants in the Simple-Certain condition who switched, (SCO , $M = 100.48$) spent significantly less time until the decision was made to stay or switch than those in the Hard-Certain conditions who switched (HC0, $M = 137.72$, $p < .001$) and than those who did not (HC1, $M = 126.42$, , $p =.005$), than those in the Hard-Uncertain condition who did not switch (HUO, M = 143.29, $p < .001$), than those who did (HU1, M = 131.97, $p < .001$). Participants in the Simple-Certain condition who switched (SC1, $M = 114.12$) spent significantly less time until the decision was made to stay or switch than those in the Hard-Certain conditions who did NOT switch (HC0, $M = 137.72$, $p = .01$). Participants in the Simple-Uncertain condition who did not switch (SU0, M = 101.15) spent considerably less time than those in the Hard-Certain condition who switched (HC1, M = 126.42, $p < .001$), than those in the Hard-Uncertain condition who did not switch (HU0, M = 143.29, $p < .001$), and than those who did (HU1, M = 131.97, $p < .001$).

Participants in the Simple-Uncertain condition who switched spent (SU1, M = 98.70) significantly less time than those in the Hard-Certain condition who did not switch (HC0, M = 137.72), than those who did (HC1, M = 126.42), and compared to those in the Hard-Uncertain condition who switched (HU1, M = 131.97) or did not (HU0, M = 143.29).

Time: Trial Completion

A post hoc analysis using the Bonferroni correction indicated that the ***average time spent to complete trial 2*** was significantly different in the following cases:

HC1 spent less: HC0, HU0
SCO spent less: HC0, HU0
SC1 spent less: HC0, HU0SU): HC0, HU0, HU1
SU1 spent less: HC0, HC1, HU), HU1

COIN ANALYSES

Statistical Analysis: Kruskal-Wallis H, Dunn's Test, Benjamini-Hochberg correction

Hard Conditions

Utilized Resource: Coins				
Condition Description	**Condition Code**	**N**	**Until Switch Mean**	**Trial Completion Mean**

Simple-Certain, did NOT switch	**SC0**	53	18.75	64.64
Simple-Certain, switched	**SC1**	33	18.39	55.03
Simple-Uncertain, did NOT switch	**SU0**	60	18.57	64.10
Simple-Uncertain, switched	**SU1**	32	18.99	54.88
Hard-Certain, did NOT switch	**HC0**	48	18.85	65.12
Hard-Certain, switched	**HC1**	38	19.45	57.89
Hard-Uncertain, did NOT switch	**HU0**	46	19.65	66.35
Hard-Uncertain, switched	**HU1**	32	20.16	57.87
	Total	**342**		

The coins spent prior to the switch opportunity and total spent in each trial were not normally distributed (Shapiro-Wilk's test, $p < 0.001$). As such, the Kruskal-Wallis H test with Benjamini-Hochberg correction was used to analyze the data. All tests were asymptotic, and the significance level was set to .05.

Coins: Start of trial until Switch

A Kruskal-Wallis H test showed there was a statistically significant difference in coins spent to switch, $\chi^2(3, N = 344) = 141.26$, $p = 0.00$ and in the total coins spent to complete Trial 1
$\chi^2(3, N = 344) = 173.48$, $p = 0.00$.

A Dunn's post hoc test with Benjamini-Hochberg correction for False Detection Rate (FDR) was conducted on the coins spent until the switch opportunity was presented. Participants in the **Uncertain-Simple condition who did NOT switch** (US0, $M = 17.70$, FDR, $p = 0.02$) spent significantly less than those in the Uncertain-Hard condition who switched (UH1, $M = 20.66$, FDR, $p = 0.02$) or did NOT (UH0, $M = 19.89$, FDR, $p = 0.02$), those in the Certain-Hard condition who switched (CH1, $M = 20.33$, FDR, $p = 0.02$), and those in the Uncertain-simple condition who switched (US1, $M = 18.60$, FDR, $p = 0.04$).

These results are interesting, particularly because participants in the simple condition spent less than those in the hard condition which indicates the cypher and key difficulty manipulation had an effect. However, the results do not appear to support the hypothesis that participants will switch less when increased mental effort is invested on a task, nor do they support that switching to a new task will occur more frequently in situations where certainty is greater about the reduction in overall resource investment to complete the project or task. The fact that participants in the Uncertain-Simple condition who did NOT switch spent significantly less than those who did might allude to the possibility of an underlying mechanism related to effort aversion. In other words, participants who struggled more with the task may have switched portals because the cyphers could be easier.

Participants in the **Certain-Simple condition who switched** (CS1, $M = 17.93$) spent significantly less than those in Certain-Hard conditions who switched (CH1, $M = 20.33$, FDR, $p = 0.02$) or did not (CH0, $M = 20.63$, FDR, $p = 0.02$), those in the Uncertain-Hard conditions who switched (UH0, $M = 19.89$, FDR, $p = 0.02$) or did not (UH1, $M = 20.66$, FDR, $p = 0.02$), and those in the Uncertain-Simple condition who switched (US1, $M = 18.60$, FDR, $p = 0.05$).

Again, it is interesting that we found a significant difference between participants in the Certain-Simple condition and those in the Uncertain-Simple condition who switched. Pragmatically, due to the design of the two portals (i.e., the cyphers in the switch portal were shorter and easier to solve) there should be no difference related to the certainty of the switch message and how many coins were spent.

Participants in the **Certain-Simple condition who did NOT switch** (CS0, $M = 18.04$) spent significantly less than those in participants in the Certain-Hard conditions who switched (CH1, $M = 20.33$, FDR, $p = 0.02$) or did not (CH0, $M = 20.63$, FDR, $p = 0.02$), and participants in the Uncertain-Hard conditions who switched (US1, $M = 18.60$, FDR, $p = 0.02$) or did not (UH0, $M = 19.89$, FDR, $p = 0.02$).

Participants in the **Uncertain-Simple condition who switched** (US1, $M = 18.60$) spent significantly less than those participants in the Uncertain-Hard conditions who switched (UH1, $M = 20.66$) or did not (UH0, $M = 19.89$, FDR, $p = 0.02$), and those in the Certain-Hard conditions who switched (CH1, $M = 20.33$, FDR, $p = 0.02$) or did not (CH0, $M = 20.63$, FDR, $p = 0.02$).

Combined result for Certain-Simple who did NOT switch, and Uncertain-Simple who did: These results are consistent with our theory that in the difficulty manipulation, hard conditions would require more mental effort and effect the number of coins spent (e.g. errors made). Regardless of the decision to switch portals or not, participants in the Simple conditions spent less than those in the Hard conditions.

Coins: Total spent in trial

Participants in the **Certain-Simple condition who switched** (CS1, $M = 55.67$) spent significantly less to complete Trial 2 than those participants in the Uncertain-Hard conditions who switched (UH1, $M = 60.31$, FDR, $p = 0.02$) or did not (UH0, $M = 65.59$, FDR, $p = 0.02$), than those in the Certain-Hard condition who did NOT switch (CH0, $M = 67.17$, FDR, $p = 0.02$), those in the Certain-Simple condition who did NOT switch (CS0, $M = 64.57$, FDR, $p = 0.02$), and those in the Uncertain-Simple condition who did NOT switch (US0, $M = 62.81$, FDR, $p = 0.02$).

From these results showing the total coins spent to complete the trial, we gather a more complete picture of participants' behavior. In line with our theorized outcome, we find that those in the Certain-Simple condition who switched spent less compared to the conditions shown above.

Participants in the **Uncertain-Simple condition who switched** (US1, $M = 56.75$) spent significantly less to complete Trial 2 than those participants in the Uncertain-hard condition who switched (UH1, $M = 60.31$, FDR, $p = 0.05$) or did not (UH0, $M = 65.59$, FDR, $p = 0.02$), those in the Uncertain-Simple condition who did NOT switch (US0, $M = 62.81$, FDR, $p = 0.02$), those in the Certain-Hard condition who switched (CH0, $M =$

67.17, FDR, $p = 0.02$), and those in the Certain-Simple condition who did NOT switch (CS0, $M = 64.57$, FDR, $p = 0.02$). Like the results above regarding switching, whether in the certain or uncertain conditions, participants spent significantly less than the other conditions shown above.

Participants in the **Certain-Hard condition who switched** (CH1, $M = 58.41$) spent significantly less to complete Trial 2 than those participants in the Uncertain-Simple (US0, $M = 62.81$, FDR, $p = 0.02$) and Certain-Simple (CS0, $M = 64.57$, FDR, $p = 0.02$) conditions who did NOT switch and the Uncertain-Hard (UH0, $M = 65.59$, FDR, $p = 0.02$) and Certain-Hard condition who did NOT switch (CH0, $M = 67.17$, FDR, $p = 0.02$).

Thus, we see that while the certainty of the switch message did not have an effect, the participants in the Certain-hard condition who switched spent significantly less than the other conditions show above. According to the Sunk Cost Fallacy, switching should always result in resource savings.

Participants in the **Uncertain-Hard condition who switched** (UH1, $M = 60.31$) spent significantly less to complete Trial 2 than those participants in the Certain-Simple condition who did NOT switch (CS0, $M = 64.57$, FDR, $p = 0.02$), those in the Certain-Hard condition who did NOT switch (CH0, $M = 67.17$, FDR, $p = 0.02$), and the Uncertain-Hard condition who did NOT switch (UH0, $M = 65.59$, FDR, $p = 0.02$).

Thus, we see that while the certainty of the switch message did not have an effect, the participants in the Uncertain-hard condition who switched spent significantly less than the other conditions show above. According to the Sunk Cost Fallacy, switching should always result in resource savings.

Participants in the **Uncertain-Simple condition who did NOT switch** (US0, $M = 62.81$) spent significantly less to complete Trial 2 than those participants in the Certain-Hard condition who did NOT switch (CH0, $M = 67.17$, FDR, $p = 0.02$) and those in the Uncertain-Hard condition who did NOT switch (UH0, $M = 65.59$, FDR, $p = 0.04$). Along with the overall trends we see in these data, the simple conditions required less resources than the hard conditions, regardless of the certainty of the switch message.

APPENDIX K

EXPERIMENT 1 AND 2 PASSPHRASES, SOLUTIONS, AND KEYS

Experiment 1 and 2 Passphrases (cyphers), solutions, keys, and portal switch cost

Experiment 1

Practice

Cypher	**Solution**	**Key**	**Length**
bimxg	sdeob	9,5,8	5

C#1 - Trial 1 - No switch				
Cypher	**Solution**	**Key**	**Length/ Coin Cost**	**Carry**
cwurm	atppj	2,3,5	5	5
kxbiefo	duzbbdh	7,3,2	7	2
apoqoejly	yklojbhgv	2,5,3	9	0
nabfdhj	hxzzafd	6,3,2	7	0
djfzqojgbq	yhcuoleeyl	5,2,3	10	0
rgnxjutfe	pdivgprcz	2,3,5	9	0
ucjryln	oaglwih	6.2.3	7	0
			54	7

C#1 - Trial 1 - Switch					
Cypher	**Solution**	**Key**	**Length/ Coin Cost**		
sciwe	qzdub	2,3,5	5		
kfwcw	dcuvt	7,3,2	5		
dvaer	bqxcm	2,5,3	5		
hsvit	bptcq	6,3,2	5		
ejzai	zhwvg	5,2,3	5		
rptjq	pmohn	2,3,5	5		
mzawg	fwypd	7,3,2	5	**Carry**	**Ttl.**
			35	7	42

C#1, Trial 2 - Switch

Cypher	Solution	Key	Length/ Coin Cost	Carry	Ttl.
leguc	izerx	3,5,2	5		
gopcg	bmmxe	5,2,3	5		
hawxp	dtuti	4,7,2	5		
nqrog	kkpla	3,6,2	5		
ixtdr	dvqyp	5,2,3	5		
uzdbq	rubyl	3,5,2	5		
zfnxk	vyltd	4,7,2	5		
			35	9	44

C# 1 - Trial 2 - No switch				
Cypher	**Solution**	**Key**	**Length/ Coin Cost**	**Carry**
ohwqxtl	heujure	7,3,2	7	7
acsjg	yxphb	2,5,3	5	2
cldnvrfu	wibhspzr	6,3,2	8	0
ehicbzanwi	zffxzwvltd	5,2,3	10	0
ywtuokhkz	wtoslffhu	2,3,5	9	0
yaswdhg	sypqbea	6,2,3	7	0
tcopevmqw	rzjnbqknr	2,3,5	9	0
			55	9

Experiment 2

Practice

Cypher	Solution	Key	Length
bimxg	sdeob	9,5,8	5

Hard-Certain/Uncertain

C#2 - Trial 1 - No Switch (Hard)					
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**	**Carry**
0	brazvdtb	zovxsyry	2,3,5	8	8
0	ndybvset	gawusqxq	7,3,2	8	8
0	oawemjjdk	mvtchghyh	2,5,3	9	1
0	hdtekiy	baryhgs	6,3,2	7	0
0	comjizdmnbu	xmjegwykkws	5,2,3	11	0
0	ywtuokhzk	wtoslffwf	2,3,5	9	0
0	munkaflo	gskeycfm	6,2,3	8	0
				60	17

C#2 - Trial 1 - Switch (Hard)						
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**		
0	sciwe	qzdub	2,3,5	5		
0	kfwcw	dcuvt	6,3,2	5		
0	dvaer	bqxcm	7,3,2	5		
0	hsvit	bptcq	2,3,5	5		
0	ejzai	zhwvg	6,2,3	5		
0	rptjq	pmohn	2,3,5	5		
0	mzawg	fwypd	5,2,3	5	**Carry**	**Ttl.**
				35	17	52

C#2 - Trial 2 - No Switch (Hard)					
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**	**Carry**
0	khioidryp	deghfbkvn	7,3,2	8	8
0	pjngdrluk	nekeyojph	2,5,3	8	8
0	rgnxjutfe	ldlrgsncc	6,3,2	9	1
0	aniosyhhhu	vlfjqvcfep	5,2,3	10	0
0	gtwobrzfv	eqrmymxcq	2,3,5	9	0
0	rogihfp	lmdcfcj	6,2,3	7	0
0	ismhlilcv	gphfidjzq	2,3,5	9	0
				60	17

C#2 - Trial 2 - Switch (Hard)						
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**		
0	leguc	izerx	3,5,2	5		
0	gopcg	bmmxe	5,2,3	5		
0	hawxp	dtuti	4,7,2	5		
0	nqrog	kkpla	3,6,2	5		
0	ixtdr	dvqyp	5,2,3	5		
0	uzdbq	rubyl	3,5,2	5		
0	zfnxk	vyltd	4,7,2	5	**Carry**	**Ttl.**
				35	17	52

Simple-Certain/Uncertain

C#2 - Trial 1 - No Switch (Simple)					
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**	**Carry**
3	drydtyct	boxbqxaq	2,3,1	8	8
3	bkjrnjbn	aigqlgal	1,2,3	8	8
3	aqwahmbqw	xovxflyov	3,2,1	9	1

2	ucxucgj	sbusbdh	2,1,3	7	0
4	ygmncrwgmyc	xejmaovejxa	1,2,3	11	0
3	crgjtojrg	zpfgrngpf	3,2,1	9	0
3	scfgvfsc	racftcra	2,1,3	8	0
				60	17

Red text are matched pairs.

C#2 - Trial 1 - Switch (Simple)						
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**		
1	dkrxk	ciowi	1,2,3	5		
1	chscj	zfrzh	3,2,1	5		
1	pdzmd	ncwkc	2,1,3	5		
1	aqunq	yntln	2,3,1	5		
1	raerz	qybqx	1,2,3	5		
1	gmitm	dkhqk	3,2,1	5		
1	fozfu	dnwdt	2,1,3	5	**Carry**	**Ttl.**
				35	17	52

C#2 - Trial 2 - No Switch (Simple)					
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**	**Carry**
3	zjziqziq	yhwhowho	1,2,3	8	8
3	hemjemhd	eclgcleb	3,2,1	8	8
3	obpemjemp	mamclgclm	2,1,3	9	1
4	kgseyskgwe	idrcvridvc	2,3,1	10	0
3	tkxbirbkx	siuagoaiu	1,2,3	9	0
2	dufdwfn	aseauek	3,2,1	7	0
3	wxowkaeko		2,1,3	9	0
				60	17

C#2 - Trial 2 - Switch (Simple)						
Matches	**Cypher**	**Solution**	**Key**	**Length/ Coin Cost**		
1	ppxkp	nmwim	2,3,1	5		
1	axpae	zvmzc	1,2,3	5		
1	dlfdi	ajeag	3,2,1	5		
1	rkopk	pjlnj	2,1,3	5		
1	gkxgs	fiufq	1,2,3	5		
1	mlxjl	jjwgj	3,2,1	5		
1	cmqym	alnwl	2,1,3	5	**Carry**	**Ttl.**
				35	17	52

APPENDIX L

POST-SESSION SURVEY RESULTS

Post-Session Survey Results

Question Prompt: ***Do you know modular arithmetic?***

Experiment 1

	Know mod?	%
EU	Yes - use every day	3%
	Yes, don't use	15%
	Learned	10%
	Don't know	71%
	Other	2%

Table xx. Post-Session Survey, Question Response. Modular arithmetic. Early-Uncertain condition

	Know mod?	%
EC	Yes - use every day	11%
	Yes, don't use	16%
	Learned	29%
	Don't know	44%
	Other	0%

Table xx. Post-Session Survey, Question Response. Modular arithmetic. Early-Certain condition

	Know mod?	%
LU	Yes - use every day	6%
	Yes, don't use	12%
	Learned	28%
	Don't know	54%
	Other	0%

Table xx. Post-Session Survey, Question Response. Modular arithmetic. Late-Uncertain condition

	Know mod?	%
LC	Yes - use every day	22%
	Yes, don't use	16%
	Learned	19%
	Don't know	43%
	Other	0%

Table xx. Post-Session Survey, Question Response. Modular arithmetic. Late-Certain condition

Question Prompt: ***Do you know modular arithmetic?***

Experiment 2

	Know mod?	%
SU	Yes - use every day	12%
	Yes, don't use	11%
	Learned	28%
	Don't know	49%
	Other	1%

Table xx.

	Know mod?	%
SC	Yes - use every day	5%
	Yes, don't use	9%
	Learned	23%
	Don't know	63%
	Other	0%

Table xx.

	Know mod?	%
HU	Yes - use every day	24%
	Yes, don't use	12%
	Learned	18%
	Don't know	46%
	Other	0%

Table xx.

	Know mod?	%
HC	Yes - use every day	18%
	Yes, don't use	16%
	Learned	20%
	Don't know	46%
	Other	0%

Table xx.

Chance Questions. Results by condition.
Experiment 1

	Question	Response	%
EU	Chance 1	A	17%
		*B	83%
	Chance 2	A	33%
		*B	67%
	Chance 3	A	7%
		*B	93%
	Chance 4	*A	55%
		B	43%

Table xx. Early-Uncertain condition, preferred choices are indicated with an asterisk.

	Question	Response	%
EC	Chance 1	A	18%
		*B	82%
	Chance 2	A	35%
		*B	65%
	Chance 3	A	9%
		*B	91%
	Chance 4	A	48%
		*B	52%

Table xx. Early-Certain condition, preferred choices are indicated with an asterisk.

	Question	Response	%
LU	Chance 1	A	23%
		*B	77%
	Chance 2	A	41%
		*B	59%
	Chance 3	A	12%
		*B	88%
	Chance 4	*A	57%
		B	43%

Table xx. Late-Uncertain condition, preferred choices are indicated with an asterisk.

	Question	Response	%
LC	Chance 1	A	33%
		*B	66%
	Chance 2	A	26%
		*B	74%
	Chance 3	A	19%

		*B	81%
	Chance 4	*A	51%
		B	49%

Table xx. Late-Certain condition, preferred choices are indicated with an asterisk.

Experiment 2

	Question	Response	%
SU	Chance 1	A	18%
		*B	82%
	Chance 2	A	22%
		*B	78%
	Chance 3	A	33%
		*B	67%
	Chance 4	A	25%
		*B	75%

Table xx. *Same as EC in Cypher 1.

	Question	Response	%
SC	Chance 1	A	22%
		*B	78%
	Chance 2	A	33%
		*B	67%
	Chance 3	A	5%
		*B	95%
	Chance 4	*A	53%
		B	47%

Table xx. *Same as EU, LU, and LC in Cypher 1.

	Question	Response	%
HU	Chance 1	A	33%
		*B	67%
	Chance 2	A	31%
		*B	69%
	Chance 3	A	23%
		*B	77%
	Chance 4	*A	52%
		B	48%

Table xx. *Same as EU, LU, and LC in Cypher 1.

	Question	Response	%
HC	Chance 1	A	25%

		*B	75%
	Chance 2	A	28%
		*B	72%
	Chance 3	A	6%
		*B	94%
	Chance 4	*A	56%
		B	44%

Table xx. Same as EU, LU, and LC in Cypher 1.

APPENDIX M

INTER-TRIAL SURVEY RESULTS BY CONDITION

Inter-Trial Survey Results by Condition

Experiment 1

	Did enjoy?	%	How difficult?	%	Why switch?	%
EU	no	6%	easy	28%	faster	72%
	yes	70%	moderately easy	56%	easier	26%
	indifferent	24%	moderately hard	15%	bored	0%
	don't know	0%	hard	0%	don't know	0%
	other	0%	free	0%	other	2%

Table x. Inter-Trial Survey. Early-Uncertain condition

	Did enjoy?	%	How difficult?	%	Why switch?	%
EC	no	4%	easy	25%	faster	60%
	yes	83%	moderately easy	61%	easier	34%
	indifferent	12%	moderately hard	14%	bored	1%
	don't know	1%	hard	0%	don't know	0%
	other	0%	free	0%	other	5%

Table x. Inter-Trial Survey. Early-Certain condition

	Did enjoy?	%	How difficult?	%	Why switch?	%
LU	no	8%	easy	20%	faster	63%
	yes	77%	moderately easy	58%	easier	31%
	indifferent	14%	moderately hard	21%	bored	4%
	don't know	1%	hard	0%	don't know	2%
	other	0%	free	0%	other	4%

Table x. Inter-Trial Survey. Late-Uncertain condition

	Did enjoy?	%	How difficult?	%	Why switch?	%
LC	no	2%	easy	33%	faster	47%
	yes	88%	moderately easy	53%	easier	51%

	indifferent	9%	moderately hard	11%	bored	0%
	don't know	0%	hard	2%	don't know	1%
	other	1%	free	0%	other	1%

Table x. Inter-Trial Survey. Late-Certain condition

Experiment 2

	Did enjoy?	%	How difficult?	%	Why switch?	%
SU	no	3%	easy	27%	faster	66%
	yes	88%	moderately easy	63%	easier	32%
	indifferent	12%	moderately hard	13%	bored	0%
	don't know	0%	hard	0%	don't know	1%
	other	0%	other	0%	other	4%

Table xx.

	Did enjoy?	%	How difficult?	%	Why switch?	%
SC	no	5%	easy	14%	faster	64%
	yes	80%	moderately easy	65%	easier	30%
	indifferent	12%	moderately hard	17%	bored	0%
	don't know	0%	hard	0%	don't know	2%
	other	0%	other	1%	other	4%

Table xx.

	Did enjoy?	%	How difficult?	%	Why switch?	%
HU	no	9%	easy	23%	faster	64%
	yes	83%	moderately easy	52%	easier	30%
	indifferent	7%	moderately hard	21%	bored	0%
	don't know	1%	hard	3%	don't know	1%
	other	0%	other	0%	other	4%

Table xx.

	Did enjoy?	%	How difficult?	%	Why switch?	%
HC	no	5%	easy	33%	faster	63%
	yes	87%	moderately easy	40%	easier	31%
	indifferent	8%	moderately hard	27%	bored	1%
	don't know	0%	hard	0%	don't know	0%
	other	0%	other	0%	other	5%

Table xx.

APPENDIX N

PORTAL SWITCH COST CALCULATION

		SERVER A				SWITCH INTERVAL			SERVER B				
		Stay Running Cost	Running Total Solved on Server A	Solved - STAY	**Cypher Length**	Switch Interval at Character *n*	Running Cost @ Switch	Condition	**Cypher Length**	Solved - SWITCH	Running Total Solved on Server B	EARLY Switch Running Cost	LATE Switch Running Cost
Trial 1	**START**	5	1	1	5				5	1	1	**12**	**18**
		12	2	1	7	**2**	**7**	**Early = 5**	5	1	2	**17**	**23**
		21	3	1	9	**1**	**13**	**Late = 5**	5	1	3	**22**	**28**
		28	4	1	7				5	1	4	**27**	**33**
		38	5	1	10				5	1	5	**32**	**38**
		47	6	1	9				5	1	6	**37**	**43**
		54	7	1	7				5	1	7	**42**	**48**
Trial 2	**START**	7	1	1	7				5	1	1	14	**18**
		12	2	1	5	**2**	**9**	**Early = 5**	5	1	2	19	**23**
		20	3	1	8	**1**	**13**	**Late = 5**	5	1	3	24	**28**
		30	4	1	10				5	1	4	29	**33**
		39	5	1	9				5	1	5	34	**38**
		46	6	1	7				5	1	6	39	**43**
	END	55	7	1	9				5	1	7	44	**48**