Enigma*

– Preliminary & incomplete, do not circulate –

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Abstract

I study military intelligence during World War II, focusing on decoded Enigma messages in the *Battle of the Atlantic*. When the Allies gained access to Nazi submarine (U-boat) information, Allied merchant ship losses declined substantially, but U-boat losses increased only partly. Strikes were selective, prioritizing high-capacity U-boats, and increased toward the end of the war. This is consistent with a mechanism of strategically foregoing benefits to safeguard the secret of information access. Counterfactual simulations indicate that Enigma intelligence prevented 40 percent of potential shipping losses, highlighting the value of military intelligence.

Keywords: : Military Intelligence, World War II, Enigma

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1 Introduction

Access to secret information can be a powerful advantage. During World War II, Allied intelligence regularly intercepted and decrypted Nazi communications. Messages provided insights into enemy strategies and movements. But the information obtained posed the Allies with a difficult dilemma: acting on it could reveal the source to the enemy, while restraint meant forgoing valuable opportunities to act.

In this paper, I quantify the effects of information access on conflict outcomes, focusing on the *Battle of the Atlantic*—one of the most pivotal campaigns of World War II. The campaign staged Allied ships, essential for maintaining supply lines, against Nazi submarines (U-boats). As Churchill (1952, p.6) famously noted,

> "[t]he Battle of the Atlantic was the dominating factor all through the war. Never for one moment could we forget that everything happening elsewhere, on land, at sea, or in the air, depended ultimately on its outcome [...]."

U-boats frequently revealed their positions through messages encrypted with Enigma machines—codes the Nazis believed to be safe.[1] When the Allies succeeded in breaking these ciphers, they faced a choice: whether to reroute and save ships in danger or even attempt to sink U-boats. Acting, however, ran the risk of alerting the enemy and losing access to future information.

I pursue two main objectives. First, I explore the trade-off involved in using intelligence—defined as the collection and application of covert information—while minimizing the risk of exposing the source. Drawing on a simple asymmetric information model, I demonstrate how this mechanism can help explain high-stakes conflict patterns. Newly collected data suggest that information was used extensively for evasive routing of Allied merchant ships, but more selectively to strike against Nazi U-boats. Second, drawing on reduced-form evidence, and a semi-structural simulation framework, I quantify the aggregate benefits of Enigma intelligence in the Battle of the Atlantic. I find that the flow of information contributed to saving 412 additional ships from December 1942 until the end of the war. This represents a 40 percent reduction in shipping losses

[1]The Allies' success remained secret even until 1974 when it was revealed in "The Ultra Secret" by F.W. Winterbotham.

and over $15 billion savings in shipbuilding cost.[2]

Enigmas were sophisticated encryption devices. Theoretically, they allowed for up to 150 thousand-trillion different settings and encoding schemes (Kohnen, 1999, p. 58). Knowing the correct settings, a receiver could recover the initial text from encrypted text. Contrary to popular belief, different versions and different networks were used across theaters of war and military units. Here, I focus on the naval Enigma employed solely by the U-boats, the *Shark* network. In this network, settings were updated daily, precisely at noon.

In the early stages of the war, the Allies lacked the capability to decrypt U-boat communications. That changed in May 1941, largely by chance (Beesly, 1977, p. 71). The Allies successfully recovered codebooks from a conquered U-boat, which allowed for real-time decryption over several weeks. More importantly, this episode helped code-breakers to learn, and to identify patterns, that would allow codes to be broken even in the absence of current codebooks. While a new version of the Enigma temporarily disrupted Allied decryption efforts in February 1942, this setback was overcome by December 1942 (Budiansky, 2000, Appendix A). From that point until the end of the war, U-boat codes were often broken within a few hours or days.

Quantifying the effects of intelligence is far from trivial as precise measurement is a key bottleneck. Intelligence is often intangible, embedded in confidential decisions that remain unobserved. This issue is particularly relevant to World War II. Instructions derived from Enigma decrypts were typically shared verbally or, if in writing, often disposed of after use (Syrett, 1983). Key war diaries and documents have also been destroyed for national security reasons (Deutsch, 1978; Syrett, 2002*b*, p. 21). Questions of *if*, *when*, and *to what extent* information was used or deliberately left unexploited remain largely unanswered (e.g. Bennet 1989, p. 136).

To guide the empirical analysis, I begin with a simple model of asymmetric information between the Allies and the Nazis. In the framework, Allies can be a high or low type, denoting their access to intelligence. Their type determines their cost structure in saving merchant ships or sinking U-boats. In equilibrium, the high type underutilizes the Enigma advantage to avoid provoking Nazi security upgrades. A key element of the model is that outcomes are subject to noise and I relate

[2]USD are in present day valuation.

different outcomes to different levels of noise. From the Nazi point of view, variation in merchant shipping losses could have been subject to a myriad of causes, it was relatively noisy. U-boat losses were more precise. Nazis knew with greater accuracy positions, numbers, operations. As a result, the model predicts that the Allies would exert less restraint in saving ships but more in sinking U-boats.

With this intuition in mind, I begin with a simple piece of motivating evidence. I relate variation in daily code-breaking speed to daily merchant ship losses and U-boat sinkings. To do so, I computed the exact time required to identify Enigma keys for each day during the years 1944-45 from primary sources. I couple this data with a plausibly exogenous source of variation: a German procedural rule. While Enigma keys were changed daily (Beesly, 1977, p. 66), keys would regularly be changed only partially. So-called 'base settings' were reused every second day, coinciding with 'even' calendar days. Whenever the Germans used such 'paired settings', the number of remaining potential keys was dramatically smaller (Erskine, 1988; Wright, 2017). In newly collected data, I observe that the Allies were significantly faster in breaking a daily key on even, that is, paired days. The difference of 8 hours corresponds to roughly a quarter of the mean decryption speed. I argue that if a similar pattern exists in outcomes, it is likely due to the variation in code-breaking speed. The evidence supports this: on even calendar days 23 percent fewer Allied vessels were hit, while no similar pattern appears in U-boat sinkings.

I interpret this as first suggestive evidence that Enigma intelligence mattered. It also hints at possible restraint in leveraging information with respect to sinking U-boats. But there are two main shortcomings in this exercise. First, it does not directly link information bits with individual-level outcomes. It rather hinges on the assumption that there are no other sources of cyclical variation that can rationalize a two-day cycle, an implicit assumption I make. Second, if the benefits of intelligence emerge with some delay, a simple comparison between odd and even days will likely not capture such dynamics.

To address these drawbacks, I rely on much more granular data using detailed records of all Nazi U-boats deployed during the war. Crucially, I observe different U-boat states—on patrol, off duty, or sunk—as well as matched data on Allied merchant ships sunk. In addition, I digitized the universe of U-boat message decrypts ($n = 43,272$) spanning from December 1942 to the end of

the war—the heart of my data contribution. To do so, I developed a digitization pipeline using state-of-the-art machine learning methods. This allows me to identify the exact days on which specific U-boats revealed their locations. Essentially, I reconstruct the Allied information set in the Atlantic, day by day.

I use these data to obtain U-boat-level estimates of the effect of Enigma intelligence. The thought experiment is as follows. Compare two otherwise similar U-boats on patrol before and after one of the U-boats reveals its location. Under the assumption of parallel trends, differences in outcomes identify the effect of Enigma decryptions. Two aspects differ from canonical difference-in-differences designs. First, U-boats are typically treated multiple times throughout their lifetime. I therefore use a stacking procedure to isolate each individual treatment event. Second, besides victories over merchant ships, the other main outcome, being sunk, is of absorbing nature. Here, I can only identify differences in survival probabilities after treatment occurs. By construction, treatment and control group have not been sunk in the pre-period.

Using this stacked event-study design, I demonstrate that U-boats saw a quantitatively large decrease in victory rates against Allied merchant vessels following a location revelation. I estimate a decline of roughly 0.72 p.p. for at least five days, where the full sample mean is 0.89 p.p. This implies U-boats lose about 80 percent of their effectiveness once a location message is decrypted—a substantial decline. Pre-treatment coefficients close to zero suggest that the parallel trends assumption holds at least before treatment events. Next, I examine U-boat survival probabilities. I find that once U-boat positions are revealed they experience a highly significant but small reduction in survival probability. After five days, treated U-boats have a 1.1 p.p. lower survival rate relative to the control group. A back-of-the-envelope calculation suggests that roughly 80 U-boat sinkings resulted directly from location decrypts.

Consistent with a mechanism of selectively deploying information, these effects are accompanied by distinct and easily interpretable heterogeneities. Most of the variation in the survival reduction stems from sunk high-capacity commanders (defined as above-median experience or above-median victory fixed effects). The asymmetric information framework provides two further testable predictions. First, toward the end of the war, the loss of secrecy looms less large. Hence, restraint should be decreasing over time. The data aligns with this prediction. Location

revelations occurring later in the war are associated with relatively larger decreases in U-boat survival rates. Second, if the loss of secrecy carries a greater weight, we should expect greater restraint. I test this under the assumption that disruptions to the Atlantic supply chain were more severe for the UK than for the US. Heterogeneity by geography also corroborates this prediction: American forces are more decisive in leveraging decrypts than their British counterparts.

With these estimated effects, I move to a final exercise. I ask: how many Allied merchant ship losses did Enigma intelligence prevent *in the aggregate*? To answer this question, I develop a semi-structural simulation framework. I characterize the different states relevant for U-boats—patrolling, not patrolling, or sunk—as well as transition rates among these states. I then inform the model with the reduced form estimates to simulate counterfactual U-boat distributions. Considering two channels, the short-term reduction in U-boat effectiveness upon a location disclosure and the long-term effect of sinking U-boats, I estimate that Enigma decrypts prevented 412 merchant ship losses, a relative reduction of 40 percent, saving approximately 6,600 seamen's lives from December 1942 until the end of the war.

A simple exercise helps evaluate a first-order economic impact. Consider that the cost of building a single standard merchant ship, the Liberty, was roughly $1.8 million in the 1940's (Williams, 2014, p. 31) with a present value of roughly $38 million.[3] My estimates therefore suggest that Enigma intelligence prevented ship-building costs of over $15 billion today. Note, these benefits are directly tied to U-boats and the Battle of the Atlantic. These are lower-bound effects of Enigma intelligence. Evaluating the impact of higher arrival rates of supplies on the duration of the war are avenues for future research.

Literature. This paper speaks to different strands of literature. First, it adds to the economics of conflict. Empirical research in this field has examined various determinants of interstate conflict, including trade (Martin, Mayer and Thoenig, 2008), relatedness of populations (Spolaore and Wacziarg, 2016), natural resources (Caselli, Morelli and Rohner, 2015), recessions (Hess and Orphanides, 1995), political accountability (Conconi, Sahuguet and Zanardi, 2014), and, international alliances (Jackson and Nei, 2015). Most of these studies explore factors that either prevent

[3] I use the Minneapolis Fed inflation calculator from 1941-2024 https://www.minneapolisfed.org/about-us/monetary-policy/inflation-calculator.

or initiate conflict. A notable exception is recent work by Federle, Rohner and Schularick (2024), who focus on economic prowess. They find that exogenous financial shocks increase winning odds in military disputes. Building on this literature, I provide evidence on a hitherto empirically unexplored channel, military intelligence.

On a more conceptual level, this paper is one of few that bridge the gap between theories of asymmetric information and empirical evidence. An exception from this is work by Fetzer et al. (2021). Their paper views insurgent strategy in Afghanistan through the lens of a signaling model. In a similar vein, my work demonstrates how the threat of revealing access to Enigma information can help explain life-and-death outcomes in the Atlantic.

I also add to nascent work on the effects of intelligence more specifically. Within this realm, Sonin and Wright (2024) show how enhanced surveillance capacity is associated with more complex tactics and greater effectiveness against security forces in Afghanistan. However, their measure of intelligence is based on surveillance operations that were *exposed* by the other conflict party. This differs from the setting here where the Nazis never realized that Enigma keys were broken. Another pioneering study is Glitz and Meyersson (2020) who show that industrial espionage during the Cold War raised East German productivity. Distinctly from these two studies, I do not only focus on direct benefits but highlight the indirect limits of information that arise from dynamic considerations. Thus, I speak to both first-order and second-order effects in the use of intelligence.

Moreover, I add to research on the determinants of conflict outcomes in World War II. Most work on this theme studies individual motives downstream. For example, Ager et al. (2022) investigate peer effects among fighter pilots in World War II while Adena et al. (2021) explore how bombings and the destruction of hometowns affected pilots' morale. What separates my paper is that I study decisions at the highest levels of the Allied command chain.

On a final note, this paper relates to a tradition of economists devoted to applied research in World War II (Guglielmo, 2008). Famously, the Statistical Research Group, with members such as Harold Hotelling and Milton Friedman, aided the Allied war effort, devising methods of submarine search (Wallis, 1980). I add new perspectives on strategic decision-making.

Outline. The paper unfolds as follows. First, I provide a broad overview of the historical background in Section 2. Section 3 formalizes the key trade-off involved in weighing the use of intelligence. I then discuss data sources and construction in Section 4. Section 5 explains the empirical strategy and presents estimation results. Section 6 sets up the simulation framework and evaluates aggregate effects. Finally, Section 7 concludes.

2 Historical Background

Enigma. All major powers in the Second World War used machines to encrypt communication. The Germans predominantly relied on so-called Enigmas, with different versions and networks active across theaters of war.[4] Enigmas, at their core, were rotor machines. A given plaintext would be transformed letter by letter, depending on underlying settings. Appendix Figure A1 provides a simplified illustration of the mechanics. The receiver could then decode these texts knowing the correct settings. It was the identification of these daily changing settings, which was the key obstacle in Allied decryption efforts.

Intelligence officers employed various methods in code-breaking. The predominant technique relied on so-called cribs, small bits of guessed plain text, which allowed the reconstruction of keys. Commonly used cribs pertained to routine weather reports. For instance, specific messages consistently started with "VONVONWEWABOULOGNE" (From weather station Boulogne).[5] Matching the guessed plaintext with the encrypted letter sequence, electro-mechanical machines[6] then helped identify the underlying Enigma configurations by iteratively eliminating incorrect settings (Sebag-Montefiore 2000, p. 151-153; Budiansky 2000, p. 131).[7]

Typically, messages were intercepted at different stations around Atlantic coastlines (Syrett, 1999). These were then relayed to Bletchley Park, a country house North of London, where the bulk of

[4] Hinsley (1981, Appendix 4) provides an exemplary overview of different keys attacked by British cryptanalysts in the earlier half of WWII.

[5] In some instances, the Allies provoked Germans to send cribs unknowingly. For instance, the Royal Air Force was instructed to lay mines in designated regions prompting specific message responses (Sebag-Montefiore, 2000, p. 187).

[6] These machines, called 'bombe', were initially developed by Gordon Welchman and Alan Turing (Erskine, 1989).

[7] For precise accounts of the technical aspects of Enigma encryption and decryption I defer to Sebag-Montefiore (2000, Chapter 3), Kahn (1991, Chapter 7) and Budiansky (2000, Chapters 2&4).

decryption activities were handled.[8] Intercepts, even without the decrypted text, already carried valuable information. Using direction-finding (DF) methods radio signals could indicate rough locations of vessels.[9] However, this required several independent bearings from different stations. Moreover, signal characteristics like the length and format could indicate what type of message was being sent, e.g. a convoy sighting or a weather report (Syrett, 2002*a*). In some instances, it was even possible to identify U-boat radio operators solely through their morse-sending style (Beesly, 1977, p. 272-273).

Once settings were broken, messages were translated and sent to the Operational Intelligence Center (OIC) in London. This was where decisions were made on how to respond to novel intelligence (Beesly, 1977, p. 61-72). Roughly one third of all decrypts that arrived at the OIC contained specific information on U-boat grid positions.[10] Typically, these allowed for pinpointing vessels to 11 by 11km squares (Erskine, 1992). Appendix Figures A2 and A3 provide examples of Nazi grid maps.

U-boat warfare. In the study at hand, I focus on U-boat warfare, later referred to as the Battle of the Atlantic. The naval theater saw the longest war campaign in WWII. The Allies were shipping vast amounts of goods and resources, mainly from the Americas to the UK, later on also to the Soviet Union, while German submarines tried to intercept and sink these merchant vessels. Throughout the war, over three thousand ships were sunk by Nazi U-boats, of which 2750 were merchant and passenger ships. While German submarines were, by and large, the main threat against Allied vessels, both the Japanese and Italian Navies also deployed submarines in warfare. While the Italians sank 99 merchant vessels, predominantly in Mediterranean waters but also in the Atlantic, the Japanese accounted for roughly 244 sinkings.[11]

[8] Later in the war, Americans joined the decryption efforts. Intelligence among the Allies was generally shared on a high-frequency (Syrett, 1999). Kohnen (1999) provides an in-depth account of Anglo-American intelligence cooperation.

[9] The typical accuracy of DF estimates was an area of approximately 10,000 square miles (e.g. 100 by 100 miles) (Beesly, 1977, p. 272)

[10] Own calculations based on all U-boat messages decrypted from December 1942 until May 1945.

[11] Numbers are based on `https://uboat.net/` and Rohwer (1999). Warships etc. are excluded.

Concealing the secret. The Allies went to great lengths to maintain the secrecy of Enigma's vulnerabilities. Besides staff at Bletchley Park, only a few dozen individuals in the leadership of the Royal Navy and the US Navy had access to Enigma-derived intelligence (Beesly 1977, p. 99, Knowles 1977, Kohnen 1999, p. 78).

In the Atlantic, it was Admiralty directive that the "source must never be jeopardized by carrying out a tactical operation which might arouse the enemy's suspicion" [12]. Whenever intelligence was shared, the Allies were meticulous in creating plausible alternative explanations for successful operations. In some instances, Enigma information was reportedly only acted upon, if Air Reconnaissance activities or precise direction-finding fixes had also revealed a particular position (Knowles, 1977; Beesly, 1977, p. 90 & 101). At times, BP officials instructed the Admiralty to specifically refer to Air Recc as the source of success when talking to the press (Batey, 2011). The British also spread the rumor that they had developed a novel radar technology capable of detecting U-boats at very large distances (Hinsley, 1990).

Necessitating such *plausible deniability* raises the question of to what extent Enigma intelligence was deliberately not acted upon when alternative sources were missing. Here, the historical literature is surprisingly scarce. To the best of my knowledge, a systematic account does not exist. In one rare instance, after a series of successful attacks, Andrew Cunningham (1944), First Sea Lord, was quoted as stating "that for the present it will be most advisable to suspend operations against U-boats" (as cited in Kohnen, 2019). It is unclear, however, to what extent this thinking guided intelligence utilization throughout the war.

Historian Ralph Bennett, who also served at Bletchely Park, underlines this mechanism albeit in a different theater, Axis supply lines in the Mediterranean. He contemplates why not more Axis tankers were sunk with the help of decrypted messages, concluding "[s]ecurity measures to protect the source are perhaps the most likely explanation" (Bennett, 1996).

Ex-post, worries of revealing the compromise were indeed merited. In several instances, German officials became highly suspicious of cipher leakages, particularly after successful strikes on U-boats. Yet, despite internal investigations, it was never concluded that broken Enigma codes were

[12] ADM 223/88, "Admiralty Control in Operations".

the cause (Erskine and Weierud, 1987; Ratcliff, 1999).[13] Along this vain, it remains noteworthy that it took almost three decades until the secret of the compromise reached the public, a fact that also greatly surprised the late German U-boat admiral, Karl Dönitz:

> "So that's how it happened!... I have been afraid of this time and again. Although the experts continually proved—with conviction as it seemed—that there were other reasons for the suspect observations, they were never able to dispel my doubts completely... Only after the war did I feel reasonably reassured by the lack of any reports from the Allied side... Well, now you historians will have to start right at the beginning again!"[14]

3 Conceptual Framework

To guide the empirical analysis, I begin by formalizing the key trade-off associated with exploiting intelligence.[15] I also develop auxiliary predictions, that I later test in the data. Details and derivations are relegated to Appendix Section B.

I consider a standard asymmetric information game. There are two agents: the Allies and the Nazis. The Allies may be one of two types, high-capacity (θ^H) or low-capacity (θ^L), with the high type able to leverage superior intelligence capabilities. I conceptualize being the high type as having a lower cost in achieving desirable military outcomes (e.g., saving merchant ships or sinking U-boats). The probability, p, of being the high type is common knowledge.

The game unfolds over two periods. In the first period, the Allies choose action s_1, which we can think of as the number of merchant ships they wish to save, or U-boats to sink. The Nazis then observe $z = s_1 + \varepsilon$, a signal of the Allied choice subject to some noise. The noise is uniformly distributed with boundaries $[-\phi/2, \phi/2]$.

[13] Even in 1970 a German intelligence officer still publicly sustained the claim that U-boat ciphers were never broken (Ratcliff, 1999).

[14] Transcribed in the foreword by Jürgen Rohwer in the 2012 edition to Dönitz (1958) memoirs.

[15] To the best of my knowledge strategic restraint in intelligence utilization has not been micro-founded formally. Axelrod (1979) has characterized the use of intelligence, but as a one-agent problem assuming that 'intelligence' can only be used once and is lost thereafter.

Given the signal, the Nazis decide whether to invest in a costly security upgrade, or not. If the investment is undertaken, the Allied cost structure equals the low-type in the second period, regardless of the initial type assignment. Else, they retain their cost structure. After the Nazi decision, the Allies choose s_2 the number of merchant ships they wish to save, or U-boats to sink, in the second period. From the perspective of the first period, the second period is discounted at rate β. Finally, note, that Nazi payoffs in the first period are unaffected by their upgrading decision, but they linearly dislike increasing levels of s_2 in the final period.

I consider an equilibrium as a set of strategies by Allies and Nazis that represent best-responses to each other and beliefs by Nazis that map all signals to a Bayesian posterior about the Allied type. Under parameter assumptions that allow for an interior solution, the following describes equilibrium behavior. The Nazis adopt a cutoff rule, in which they are willing to make the costly security investment only if their Bayesian posterior about the Allied being the high-type is sufficiently high. Concretely, they upgrade if the Allies save very high numbers of ships or sink unreasonably many U-boats. The high-type Allies in the first period are aware of the upgrading behavior. To probabilistically avoid the security investment, they choose lower levels of s_1 compared to a one-period optimum as a benchmark. This essentially captures the notion of restraint in intelligence utilization.

The model generates three testable predictions.

1. **Restraint decreases with noise.** Consider rerouting merchant ships and sinking U-boats separately. Nazis are fully aware of their U-boats, their states, positions, etc. while having an accurate sense of how many merchant ships there are and how many ought to sink is much more opaque. I conceptualize these differences through variation in the noise level ε. Comparative statics predict greater restraint in using intelligence to sink U-boats, but less restraint in rerouting and saving merchant ships.

2. **Restraint declines over time.** One can interpret β as the relative weight of the future. The weight is larger if the second period is 'longer'. Comparative statics predict that earlier in the war more information is strategically left unused than later.

3. **Restraint increases in the relative value of retaining/losing Enigma intelligence.** Under a

small extension of the baseline model, one can introduce a parameter that shifts the value of saving ships/sinking U-boats in the second period. I relate this to different valuations of the stakes by British versus American forces. Arguably, disruptions to the Atlantic supply chain loomed relatively larger for the British. Comparative statics predict greater restraint when the relative valuation is higher. We would therefore expect British forces to exploit information less.

4 Data

To test these predictions, and to perform an aggregate quantification exercise, I collected extensive data on naval warfare. This includes information on naval vessels (Allied merchant ships and Nazi U-boats) and novel data from messages encrypted with Enigma machines. This section discusses sources, dataset construction and descriptives.

4.1 Naval Vessels

The primary source of data on naval vessels is https://uboat.net/, accessed in mid-2023. The website has compiled and digitized extensive information on units related to naval warfare in World War II. To ensure data quality, I manually cross-checked selected database entries with Rohwer (1999), work by a renowned German military historian, and found the data quality to be very high.[16] In total, the records cover 3335 Allied ships sunk by Nazi U-boats.[17] To provide a sense of the geographic scope, Figure 1 illustrates the distribution of sinkings, with most occurring in the North Atlantic. For most ships, I observe the date on which a hit occurred, the associated tonnage, and the number of lives lost. For auxiliary purposes, I also gathered information on ships sunk by other Axis powers, the Japanese and Italian navies.[18]

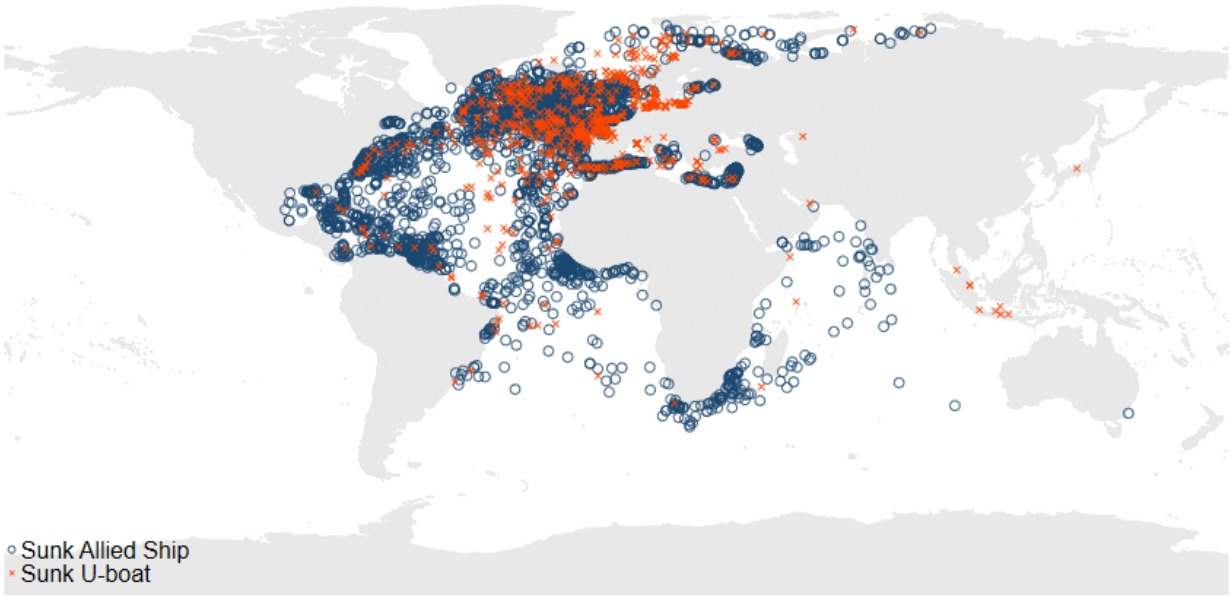
For the main analyses, I make two restrictions. First, I focus only on merchant and passenger

[16] The website has also been independently recommended by the German Submarine Museum and is an often-mentioned source in the Griffin Museum of Science and Industry, Chicago.

[17] This includes 80 events in which a vessel was heavily damaged, but not sunk, and 6 captures. For ease of exposition, I refer to all these events as "ship losses".

[18] For Japanese submarines, I digitized information from Rohwer (1999) while data on Italian submarines were also collected on https://uboat.net/.

Figure 1: Geography of the U-boat warfare.



Notes: Circles represent locations of hit Allied merchant ships by a Nazi U-Boat. Crosses indicate sunk U-boats.

ship losses ($n = 2750$), because their objectives were clearly defined: the Allies aimed to minimize losses, while the Germans sought to maximize them. This excludes primarily warships, where associated losses are more difficult to interpret (e.g. when they result from protecting merchant vessels).[19] Second, when analyzing aggregate variation in Allied decryption capacity specific to the U-boat network, *Shark*, I restrict the sample to vessels operating in respective regions. For example, I exclude merchant ships sunk by U-boats in the Mediterranean after June 1943, as these U-boats moved to their own, separate network. Notably, these geographical restrictions remove only a small fraction of sunk merchant vessels (4.1 percent).[20] However, when relying on U-boat-level variation, I do not impose geographic restrictions.

Ideally, I would also like to observe the total number of merchant vessels sailing at a given point in time—not only those that were lost. Unfortunately, I am unaware of an accessible database that records all successful WWII merchant voyages. As an imperfect measure, I collected data on the main official convoy voyages from the online compendium to Rohwer and Hümmelchen

[19] In some instances, escort vessels were intentionally sacrificed (Beesly, 1990).
[20] The precise selection process is detailed in Appendix C.1.

(2005).[21] The limitation is that this only represents a subset of all active voyages. It does not include independently sailing merchant vessels. To give a sense of the scale of missing data: among all merchant ship losses, there was a roughly equal split between independently sailing ships and those in convoy groups. Summary statistics of key variables in the time series are presented in Table 1. Across the entire war, 1.27 merchant ships were sunk every day, while close to 700 ships sailed in convoy groups.

I also collected extensive information on all Nazi U-boats from https://uboat.net/. For each unit, I observe key events, including fleet entry, active patrol periods, and ultimate fate (sunk or survived). On average, around sixty U-boats were active on a given day during the war, with one U-boat lost every three to four days in Shark-designated waters (Table 1). Importantly, for each U-boat I observe associated kills/victories over Allied ships. For 85 percent of U-boat-day observations, I also obtained geographic positions. In case of incomplete location data, I impute missing positions using the last known coordinates.

Table 1: Summary Statistics (daily time series).

	Mean	SD	Min	Max	N
Sunk merchant ships	1.27	1.89	0	15	2074
Merchant ships sailing	686	256	0	1,421	2074
Sunk tons	6,798	10,813	0	96,906	2074
Sunk U-boats	.284	.67	0	9	2074
Patrolling U-boats	59.5	37.6	2	158	2074

Notes: Summary statistics of the time series data set. Unit of observation: day. Coverage: September 1939 - May 1945, Shark regions.

For the main analysis, I construct a highly granular panel dataset at the U-boat-day level. I focus on all units on active patrol—the key object for understanding the operational impact of Enigma intelligence—between December 1942 to May 1945. During this period, U-boat codes were broken with high frequency and little delay. In total, I observe 676 U-boats going on at least one patrol (Table 2). The average U-boat commences five patrols, sinking one merchant ship over its lifetime. However, this average masks considerable heterogeneity. U-181, for instance, recorded fifteen merchant ship victories, U-510, a staggering eighteen.[22] Both U-boats also remained op-

[21] Data accessed in late 2022 on https://www.wlb-stuttgart.de/seekrieg/konvois/konvois-frames.htm. These are digitized tables from Hague (2000).
[22] Numbers relate to the sample period.

erational until Nazi Germany's surrender. Yet, these were far from common outcomes, nearly three-quarters of all U-boats were eventually destroyed while on patrol (Table 2).

Table 2: Summary Statistics of U-boats active December 1942 to May 1945.

	Mean	SD	Min	Max	N
No. patrols	4.98	4.61	1	35	676
Days patrolling (tot.)	112	93.9	2	520	676
Days location msg. decrypted	11	11.8	0	62	676
Days other msg. decrypted	17	17.1	0	101	676
Sunk merchant ships	.994	1.95	0	18	676
U-boat lost	.731	.444	0	1	676

Notes: Summary statistics for all patrolling U-boats. Coverage: December 1942 - May 1945.

Time trends. How does decryption capacity co-move with naval outcomes over time? I provide a birds-eye view in Figure 2. In Panel (a) I show monthly averages of sunk Allied merchant ships while Panel (b) shows Nazi U-boat losses. Dashed lines track the number of active merchant vessels in (a) vis-à-vis the number of patrolling U-boats in (b).[23] Both panels also display periods in which the Allies were able to break U-boat Enigma codes as light blue backgrounds.[24]

Allied cryptanalysts first managed to break U-boat ciphers in May 1941. Subsequently, traffic was read over several months with little delay. In Figure 2, perhaps surprisingly, we observe little outcome variation around the first breaking of codes. Neither does the number of sunk merchant ships decline dramatically, nor does the number of sunk U-boats increase markedly. A plausible reason: the Allies first underwent a period of learning.

In February 1942 the Germans suddenly changed their encryption system. As a result, decryption efforts were rendered unsuccessful for approximately ten months. During this time outcomes appear to respond. German merchant sinking rates increase two to three-fold—Nazis later referred to this period even as "the happy time". Somewhat unintuitively, the number of U-boat losses also increased in this period. A likely cause was the simultaneous release of more U-boats into patrol.

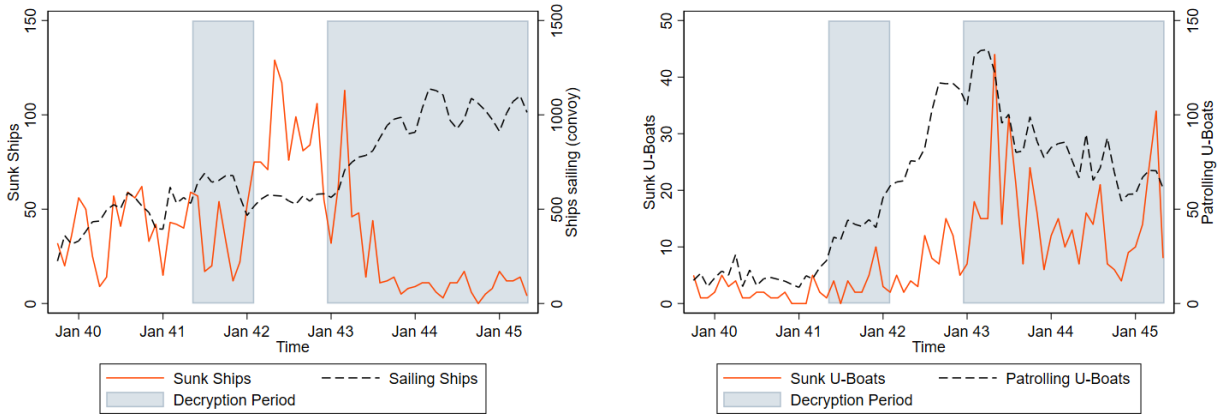
Finally, on the 14th of December 1942, the Allies eventually learned how to solve keys for the new, improved Enigma system. From one day to the other, codes were again broken with short delays,

[23] Active merchant vessels are those sailing in convoy.
[24] Precise dates are drawn from Beesly (1977, p.71) and Budiansky (2000, Appendix A).

and information was immediately translated into operational usage. At the same time, losses of merchant ships decline substantially from previously almost one hundred ships per month to less than twenty. U-boat losses continued to grow for some time and remained at a relatively high level until the end of the war.

These aggregate time patterns suggest co-movement in decryption capacity and naval conflict outcomes. One may be tempted to infer a causal relationship, but there are several concerns. Most importantly, other things were happening around key dates. For instance, higher merchant and U-boat losses in 1942 relative to before may be a result of the US officially entering the war, not the Enigma upgrade. To obtain credible causal estimates, I draw on high-frequency microdata which I discuss next.

Figure 2: Sunk merchant ships and U-boats over time.



(a) Sunk merchant ships

(b) Sunk U-boats

Notes: Left-hand panel presents the number of sunk merchant ships and ships sailing in convoys binned by months. The right-hand side shows the number of sunk and patrolling Nazi U-boats binned by months. The shaded areas indicate periods in which Enigma messages were largely decrypted.

4.2 Enigma Intelligence

The key data contribution is the collection and digitization of Enigma intelligence. I explore two sources. First, I focus on an intensive margin, i.e. how fast daily keys were broken. Specifically, I collected data from daily naval bulletins held at the National Archives, Kew, London. For close to each day starting on the 15th of November 1943 until German surrender these records allow me

to compute the number of hours the Allies required to break a new daily key. I use this type of variation to provide first evidence on the importance of Enigma intelligence. Appendix Figure C1 provides an example of a bulletin entry.

The second source, and even more granular variation, comes from original decrypted messages. I collected all U-boat decrypts from the National Archives from December 1942 until May 1945. This includes 43,272 scans available online.[25] Using state-of-the-art object detection and optical character recognition software (OCR), I then extracted key information bits: (1) specified U-boats (or their associated commanders) (2) time of record entry/decryption (3) time of interception/origin (4) whether they include geo-information. Appendix C.4 discusses the digitization process in greater detail and provides two decrypt examples. After text processing, I matched decrypts day by day with all 676 U-boats patrolling from December 1942 to May 1945.

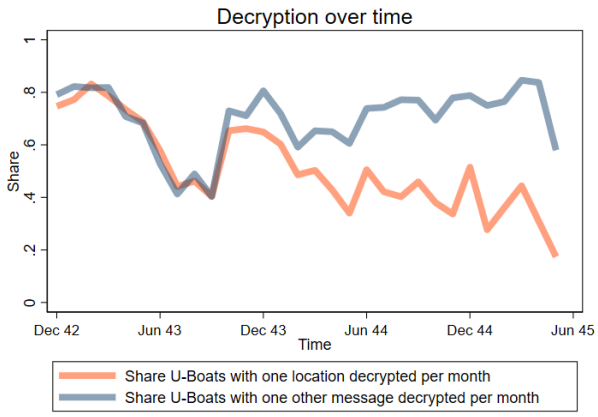
On average, I code roughly ten percent of patrol days as days on which a precise location is revealed (Table 2). Moreover, I show the monthly share of patrolling U-boats that the Allies intercepted and decrypted in Figure 3. Across the analysis period, the Allies broke at least one message per month for roughly 75 percent of all U-boats patrolling. Interestingly, the share of messages without location information remained stable over time and was not subject to a broader trend. However, the share of U-boats transmitting or receiving precise location information steadily declined from initially 70 percent in early 1943 to 30 percent in 1945—possibly an effort to reduce risk.

5 Empirical Analysis

In this section, I characterize how Enigma intelligence shaped naval war outcomes. First, I begin with motivating evidence, drawn from daily variation in code-breaking speed. Second, in the main analysis, I leverage variation from decrypts that differentially reveal U-boats. These estimates then inform the aggregate quantification exercise.

[25] Besides the National Archives in London, the National Archives at College Park, Maryland (USA) also hosts an archive of decrypts. In practice, these share the same format and content. A benefit of the American decrypts is, however, that they include notes on direction-finding and decoded grid references (Syrett, 1998, p. xxiii). The reason I collected data from the British source is their digital availability.

Figure 3: Decryption intensity over time.



Notes: Share of patrolling U-boats of which at least one message with/without location information was decrypted in a given month. Data based on the universe of decrypts December 1942 to May 1945.

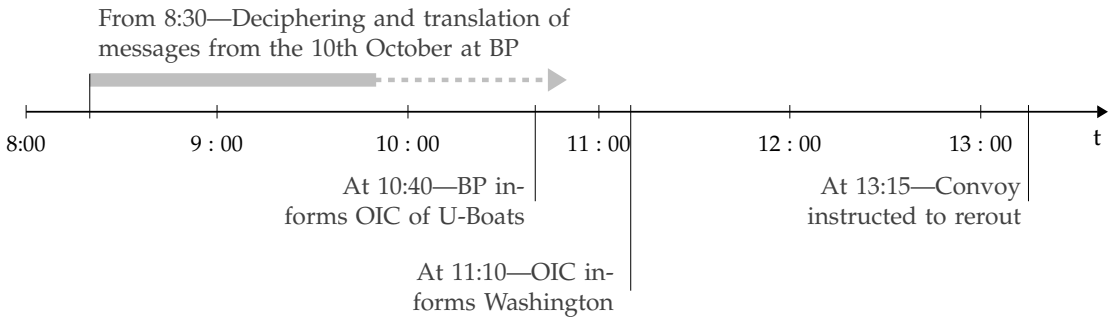
5.1 Motivating Evidence

Does the timely arrival of intelligence matter? To set the stage for a first empirical answer it is instructive to recount a few days in the journey of convoy SC48 based on work by Rohwer (1979).

Case study. Convoy SC48 started its venture on October 5, 1941, heading from Nova Scotia, Canada, toward Liverpool. Initially uneventful, the situation changed on October 12 (timeline illustrated in Figure 4). That morning, Allies had decrypted the October 10 daily key and cryptanalysts immediately began deciphering and translating messages at Bletchley Park (BP). At 10:40 am BP then relayed pivotal information to the OIC confirming the position of four Nazi U-Boats in threat of encountering SC48. Only thirty minutes later, British authorities advised Washington to reroute the convoy, which the U.S. did by 1:15 pm, ensuring the convoy's temporary safety. Within hours of a recent key break, relevant information was extracted and operational actions were almost instantly taken.

Unfortunately, convoy SC48's journey was not over yet. A few days later, on the 15th of October, the convoy encountered U-553 by chance and three vessels were subsequently lost. Instructions to U-553 and surrounding U-boats had been decrypted 26 hours too late. This episode exemplifies the importance of *timely* decryption. Next, I will quantify its importance.

Figure 4: Timeline on the 12th of October 1941



Notes: Communication chain on the 12th of October 1941. Based on Rohwer (1979).

Variation. To this end, it is useful to begin by thinking about the ideal design. In an experimentally controlled environment, one would consider the following equation:

$$y_t = \beta DecryptionTime_t + \varepsilon_t \tag{1}$$

where y_t are sunk merchant vessels/U-boats and β would capture the causal effect of decryption time for day t's key on these outcomes. In this naive specification, we would expect lower decryption time to be associated with lower merchant losses/ higher U-boat sinking. The concern with estimating the β coefficient in the setting at hand is, however, that effort and computation power, which directly affected how fast a network was broken, were reportedly reshifted among Enigma keys depending on need (Rohwer 1988, p.91; Erskine and Marks 2004; Kohnen 2019, p.281). To the extent that more effort was exerted on riskier days, a lower decryption time might even be associated with higher merchant losses. A second complication arises from the fact that the effects of decryption are not necessarily confined to the same day. If the settings from day t are identified a day later, we would naturally not expect outcomes to be affected on day t. Similarly, spillovers on subsequent days are also not accurately accounted for.

To solve these problems, I rely on a simple reduced form exercise. I draw on a peculiarity in German code-changing behavior, a procedural rule. Settings of the naval Enigma were divided into two components: inner and outer. German procedures stipulated that while the outer component should change every day, the inner component should change every *second* day (Erskine, 1988). It is not entirely clear, why this rule existed, but a likely reason was that the inner component was

only to be updated by higher-ranking officers in an effort to increase security. However, the reuse of setting components on every second day, coinciding with even calendar days, meaningfully reduced difficulty in identifying such paired daily settings (Erskine 1988; Budiansky 2000, p. 157; Wright 2017).

I use this cyclical rule as a source of regular and exogenous variation for decryption speed. I argue that if we observe a similar two-day cycle in conflict outcomes, it is likely because of the cyclicality in code-breaking speed.

Result. In the data, I first document that even calendar days had significantly faster decryption speed. Mean decryption times are depicted in Figure 5 Panel (a). I find that there is a substantial difference (8 hours) across even and odd calendar days, that corresponds to roughly a quarter of mean decryption speed (30 hours).[26] Reassuringly, the same pattern exists in the decrypt-level data (Appendix Table D2). For the decrypts, I calculate the time span from interception to being relayed to the OIC. Again, I estimate a 22-23 percent time drop from odd to even days. Importantly, this variation is mirrored in the share of messages decrypted exceptionally fast ($\leq$ 12 hours). The share amounts to 23 p.p. on odd, but 29 p.p. on even calendar days, a 23 percent difference relative to the mean.

I then proceed by showing that such a two-day cycle exists in the number of sunk merchant ships: on even calendar days, significantly fewer Allied vessels were hit by German U-Boats (Figure 5 Panel (b)).[27] I estimate a difference of about 23 percent of the mean shipping losses per day, which is equivalent to one more saved ship every six days. Note, I do not identify such a two-day pattern in periods where Enigma codes remained unbroken.[28]

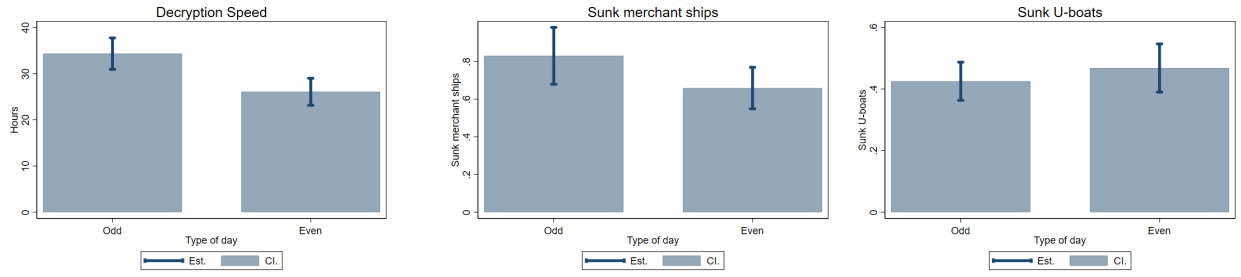
We can relate this back to Jürgen Rohwer (1979)'s exemplary case study. In the early morning hours of October 12, 1941, BP cryptanalysts broke the key from two days earlier, the 10th, an even calendar day. This relatively timely break allowed them to instruct a convoy to reroute at 1 pm on

[26] Estimates are presented in Appendix Table D1.
[27] Estimates are presented in Appendix Table D3.
[28] Placebo estimates are presented in Appendix Table D4. Note, the point estimate are similar in magnitude to the baseline two-day difference. But to interpret it, one needs to account for the much higher baseline outcome variation in no-Enigma periods. Relative to the mean, I identify an insignificant 6 percent difference in merchant ship losses from odd to even days.

the 14th. The unobserved counterfactual would be the same day but with the key being identified 8 hours later. Said convoy would then have possibly encountered U-boats. The exercise here essentially quantifies the effects of such a delay.

Note, I do not find a similarly pronounced two-day cycle in the sinking of U-Boats (Figure 5 Panel (c)).[29] One interpretation of this differential pattern is that it was a result of deliberate decision-making. The goal, to avoid greater Nazi suspicions. This would be consistent with Prediction 1 in Section 3. But an alternative explanation is that swift rerouting instructions had immediate benefits while searching and striking U-boats had a longer time lag before realization. Impacts potentially dissipated across odd and even days. In this scenario, the two-day cycle analysis may simply not identify existing effects. To conclude, the evidence suggests that intelligence mattered at least in one dimension, but the approach has clear limitations.

Figure 5: Two-day cycles in decryption speed and conflict outcomes.



(a) Decryption speed (b) Sunk merchant ships (c) Sunk U-boats

Notes: Panel (a) shows the average time to identify a daily Enigma key, for both odd and even calendar days. Panel (b) shows the average number of daily merchant ships hit by Nazi U-boats. Panel (c) shows the average number of Nazi U-boats sunk daily. Bars represent robust 95 percent confidence intervals.

5.2 U-Boat-Level Evidence

In this subsection, I shift focus to a more granular analysis, investigating how the revelation of specific U-boat locations influenced individual-level outcomes This allows me to trace out effects over time and along an extensive margin.

[29] Estimates are presented in Appendix Table D3.

Case study. To fix ideas, it is again instructive to begin with a specific case study. Syrett (1999) details the exemplary journey of U-860. The U-boat went on its maiden patrol fairly late in the war, on the 11th of April 1944, heading from Kiel through the Northern Atlantic toward the Far East. The Allies first learned of U-860's existence on the 27th of April, when it was instructed to deliver a series of weather reports. Curiously, these reports were never properly received by the Germans. They suffered from radio disturbances. Yet, the Allies received them and the radio signals helped to broadly geolocate the vessel. Eventually, on the 6th of May, U-860 was ordered to stop sending weather reports and the Allies had to rely on even rougher 'guestimation' of subsequent positions.

On the 18th of May, U-860 was directed towards West Indian waters. The Allies read the message and responded. With the intent to intercept the U-boat on its way, escort carrier USS Solomons and four accompanying destroyers left Brazil for the South Atlantic. On June 9th, U-860 broke radio silence reporting its exact position south of St. Helena in the Atlantic. The message was decrypted a day later. As a result, the Allied task group narrowed down and aircraft began searching. The first sighting was reported on the 15th of June by ensign G.E. Edwards. However, after several rounds of attacks, Edwards was fatally hit by anti-aircraft gunnery. Syrett (1999) conjectures "had [U-860] remained submerged there was the possibility that she might have escaped from the Americans". Yet, Captain Büchel, a relatively inexperienced commander, ordered the U-boat to resurface to give the anti-aircraft gunmen additional practice. After more aircraft were dispatched, rocket fire eventually delivered the *coup de grâce*, sinking U-860.[30]

A few takeaways are worth highlighting. First, messages as simple as weather reports were helpful for the Allies. While they did not necessarily allow for precisely determining a location, they enabled the Allies to learn of a U-boat's existence and subsequent channeling of resources. Secondly, even when a decrypted message revealed a U-boat's position, its fate was not immediately sealed—the Allies often searched for days before locating the vessel. Finally, while this case study is valuable in documenting a precise chain of events, it falls short in constructing counterfactual scenarios.

[30] In the collected and digitized data from the National Archive, I am able to successfully capture the key decrypts: the initial weather reports, instructions to sail toward India, and the fatal position report that led to U-860's sinking.

Empirical Strategy. To identify causal effects empirically, I employ an event-study design, constructing a reasonable control group that serves as a counterfactual. The goal is to estimate the effect of location revelations of specific U-boats on respective victory rates and own survival probability. Two characteristics in my setup differ from canonical event study designs. First, U-boats are typically treated repeatedly. I therefore use a stacked event study procedure.[31] Second, a key outcome, being sunk, is of absorbing nature. Here, I follow the health literature and identify differences in survival probabilities.

I construct the stacked estimation sample as follows. Let h denote a cohort. Each cohort consists of all U-boats treated on day h and control units. Due to the short-lived importance of location revelations, I restrict the cohort sample to a precise event window, five days before and five after h. The "clean" control units consist of all U-boats that are actively patrolling on day h but were not treated in the five preceding days or the event day itself. I then stack all h-cohort samples and estimate:

$$Y_{ith} = \underbrace{\sum_{\tau \neq -1} \alpha_\tau I^\tau_{ith}}_{\substack{\text{Event} \\ \text{Dummies}}} + \underbrace{\delta_{th}}_{\substack{h\text{-specific time} \\ \text{FE}}} + \underbrace{\gamma_{ih}}_{\substack{h\text{-specific} \\ \text{U-boat FE}}} + \varepsilon_{ith}. \tag{2}$$

Here, the outcome of interest is the number of merchant victories by U-boat i on day t in cohort h. The event study indicators are denoted I^τ_{ith} and I control for h-specific day fixed effects as well as h-specific U-boat fixed effects. Errors are clustered on U-boat level. Under the assumption of parallel trends, the estimated $\hat{\alpha}$ coefficients can be interpreted as the causal effect of location decrypts on U-boat victories over merchant vessels. Note that this approach removes 'bad'-controls (already-treated units) which may lead to biased estimates of average treatment effects in staggered treatment designs.

For the U-boat survival outcome, I can fundamentally not estimate pre-trend coefficients. The intuition is that if a U-boat is treated on day t, it can't have been sunk on any day before. I therefore estimate the following hazard model,

$$Y_{ith} = \sum_{\tau \geq 0} \alpha_\tau I^\tau_{ith} + \gamma_{ih} + \delta_{th} + \varepsilon_{ith}. \tag{3}$$

[31] This is following Rexer (forthcoming).

The outcome Y_{ith} is a dummy equal to unity unless it was sunk on day t or any day before. The remainder is as before, except that I do not estimate pre-trend coefficients.

Results. First, I discuss the effect of location decrypts on U-boat success rates. The associated event study coefficients are shown in Figure 6 Panel (a). I estimate that after a location revelation merchant victories decline by roughly 0.72 p.p. for at least five days,[32] where the full sample mean is 0.89 p.p (Table 2). This implies U-boats lose roughly 80 percent of their effectiveness once a location message is decrypted. Further, note that the pre-treatment coefficients are relatively close to zero with no clear trend evident. This suggests that the parallel trends assumption holds at least before location revelations.

Next, I examine U-boat survival probabilities. I find that once U-boat positions are revealed they experience a small but highly significant reduction in survival probability (Panel (b)). After five days, treated U-boats have a 1.1 p.p. lower survival rate relative to the control group. A back-of-the-envelope calculation suggests that roughly 80 U-boat sinkings resulted from location decrypts. This aligns in magnitude with a report that US forces sunk 93 U-boats with the aid of Enigma intelligence.[33]

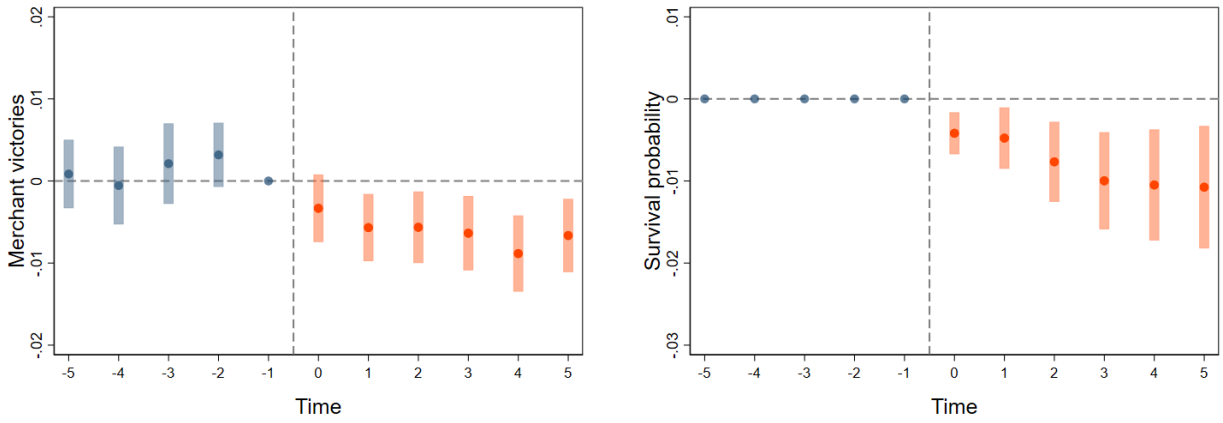
Robustness. These results are robust along several dimensions. First, one may worry about the endogenous nature of sending a location message. Consider the case that U-boats reported convoy sightings at specific coordinates. If the U-boat subsequently engaged in an attack but would be destroyed as a result, decreases in survival probability would not be caused by a location decrypt, but simply co-occur in time. First note, that this mechanism is not able to explain the fact that U-boats become less likely to sink ships, once locations are decrypted. Second, to further assuage concerns, I rerun the baseline regressions focusing only on the subset of decrypts that do not co-mention merchant convoys. This excludes convoy sightings or reported merchant victories. The estimated patterns are similar as in the main exercise (Appendix Figure D1).[34] The slight difference, pre-trend coefficients move closer toward zero.

[32] The average treatment effect is reported in Appendix Table D5.

[33] See, "*Battle of the Atlantic, Vol. I, Allied Communications Intelligence.*" p.25, Record Group 457, National Archives, College Park, Maryland.

[34] The average treatment effect is reported in Appendix Table D5.

Figure 6: Revealing positions: merchant victories and U-boat survival.



(a) Sunk merchant ships

(b) U-boat survival

Notes: Left-hand figure presents event study point estimates for the differences in victories over merchant ships by revealed U-boats versus the clean control U-boats. Right-hand figure presents survival probabilities. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

Next, I investigate robustness to the outcome variable definition. First, I re-run the baseline regression using the inverse hyperbolic sine of merchant ship victories. Estimated patterns mirror the baseline result (Figure D2 Panel (a)). I also show that, if anything, the effect increases, when adding victories over battleships to merchant ship victories (Panel (b)).[35]

Finally, I probe sensitivity to outliers. I re-estimate baseline difference-in-differences effects on subsamples while iteratively removing entire year-months. I find little variation across different point estimates, suggesting that effects are not driven by any particular time period (Appendix Figure D3).

Message content. In the next exercise, I explore the role of decrypted message content. While U-boats often communicated their coordinates, they also frequently sent messages without precise location information—for example, weather reports or fuel updates. One might consider using these messages for a *placebo* exercise. But it is ex-ante not clear how outcomes behave in relationship to such messages. The reason is that, even without explicit location details, the Allies could approximate U-boat positions through radio-signal triangulation from multiple interception sta-

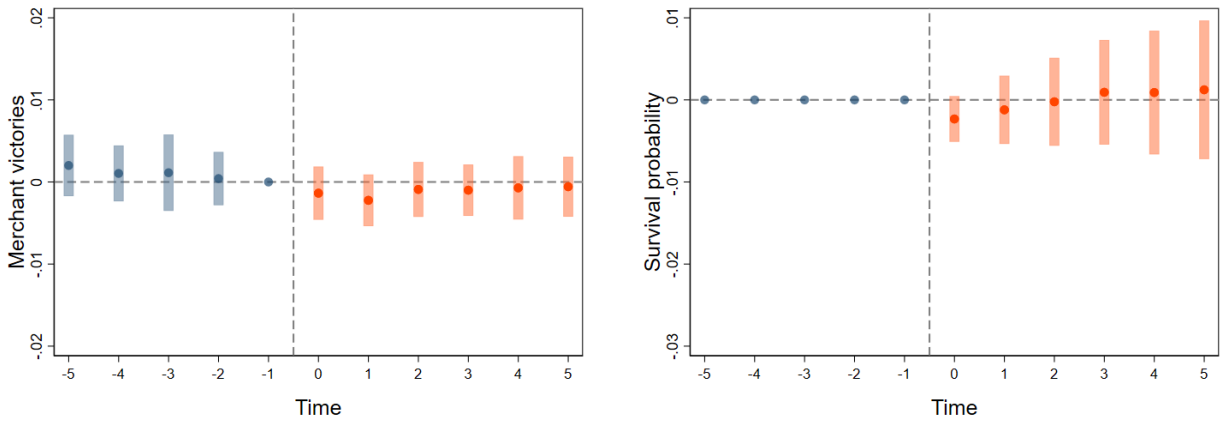
[35]The average treatment effects are reported in Appendix Table D5.

tions (high-frequency direction-finding).

I explore the quantitative importance of this channel in a similar way as in the main exercise. Specifically, I analyze all messages from U-boats that lack location information, with the decryption of these messages serving as the treatment of interest. I then construct a stacked event-study dataset as before, with one slight adjustment: I include only U-boats in an event cohort that did not send any location-bearing messages during the event day or the preceding five days. This ensures that I precisely isolate potential effects of messages without geoinformation.

Figure 7 presents the results. Panel (a) shows the event-study estimates where the outcome of interest is victories over merchant ships. Unlike messages containing coordinate information, these coefficients do not indicate substantial differences in U-boat effectiveness. In Panel (b), I present the estimated differences in survival probability. Although there is a brief decline on the exact day of message decryption, this difference fades out immediately after. Taken together, the data do not support the notion that decrypts without geoinformation had a large impact on the Allied war effort—at least locally. However, these messages may still have provided strategic value, such as improved estimates of the total number of patrolling U-boats.

Figure 7: Messages without location: merchant victories and U-boat survival.



(a) Sunk merchant ships

(b) U-boat survival

Notes: Left-hand figure presents event study point estimates for the differences in victories over merchant vessels by U-boats with placebo messages versus the control U-boats without such a message. Right-hand figure presents survival probabilities. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

5.3 Mechanism

The richness of the data allows me to study different dimensions of heterogeneity. This is useful because it allows for testing auxiliary predictions of the strategic restraint mechanism. I focus on three dimensions: U-boat capacity, time, and operational control.

U-boat capacity. First, I explore heterogeneity along U-boat capacity. The idea is that if the Allies wanted to sink some U-boats, but not all, they should eliminate those that pose the greatest danger—U-boats with experienced commanders or a record of sinking merchant ships. A condition for such precise targeting is sophisticated tracking of individual level information. The historical literature suggests that the Allies were indeed doing so. For instance, Syrett (1998, p. xxiv) documents how the Allies computed statistics on commander experience. Kohnen (2019, p. 259-260) discusses an example of how the kill history for a commander was established: U-188, lead by Siegfried Lüdden, carried specific insignia and logos on its hull. These were identified in interviews with survivors of sunk ships, allowing intelligence officers to tie ship losses to this particular U-boat.

While I am unaware of historical references prescribing selective targeting based on U-boat or commander capacity, targeting based on another dimension of value has received attention. A handful of submarines served solely the purpose of refueling other U-boats on patrol. These U-tankers were important for prolonging ongoing patrols—thereby having high value along a different margin. Late military historian Kahn (1991, p. 267) describes that it was for this reason that U-tankers were the first units to be actively targeted with the help of Enigma decrypts.

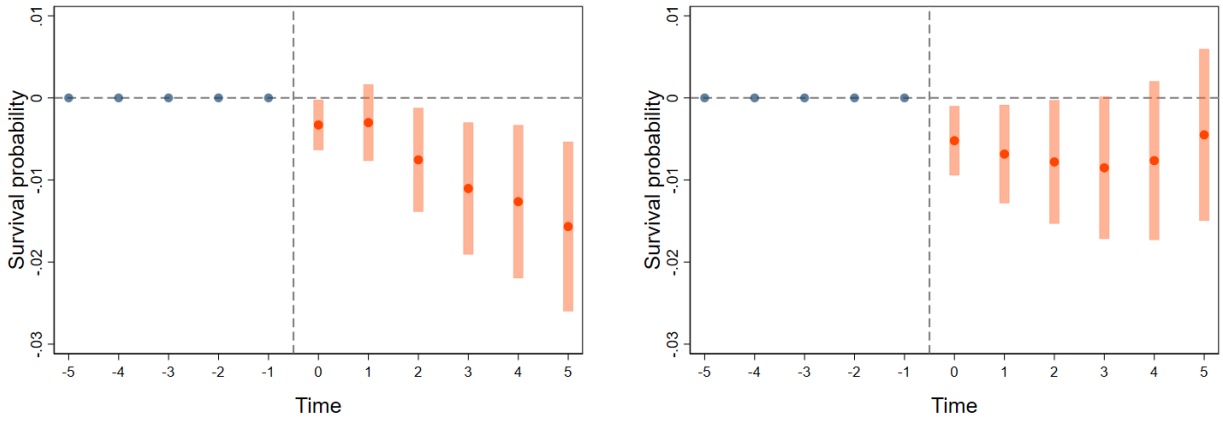
I extend this idea to a different type of value, commander capacity. To the best of my knowledge, this dimension has hitherto remained unexplored. But it comes with an empirical advantage: there is large variation across all U-boats. To measure capacity, I rely on two approaches. First, I use the number of days a commander has been on patrol as a proxy for experience. Second, I estimate commander fixed effects (FE) using victory rates over merchant vessels, arguing that these capture some variation in inherent commander quality.[36] I then split the data into above

[36]Commander FE are estimated as $Victories_{it} = Commander_i + date_t + \varepsilon_{it}$.

and below-median subsamples and estimate coefficients separately.

The estimated coefficients for the subsamples split by experience are shown in Figure 8. After five days, decrypts are associated with survival reductions of 1.6 p.p. among experienced commanders, whereas less experienced suffer a decrease of only 0.5 p.p.

Figure 8: Revealing positions: U-boat survival by experience.



(a) Above-median experience

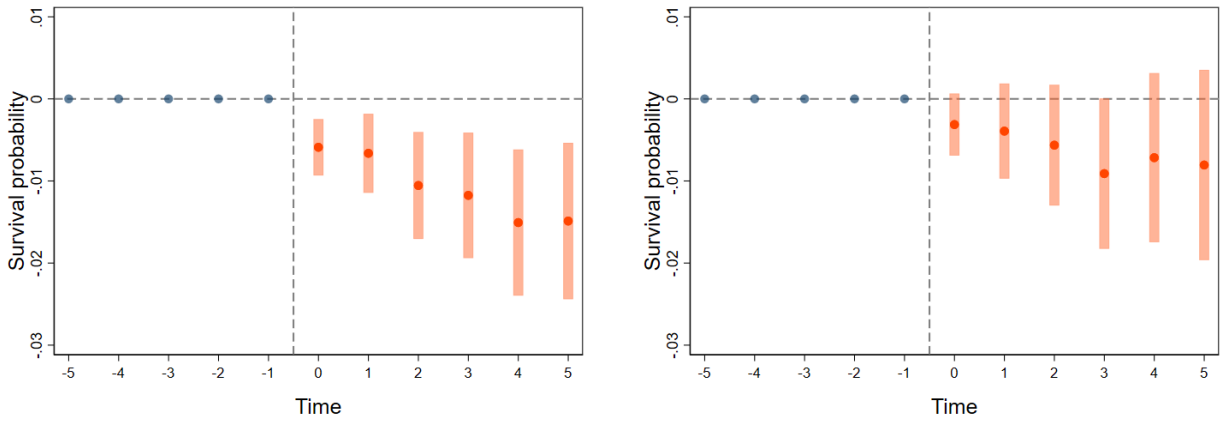
(b) Below-median experience

Notes: Figure presents event study point estimates for the differences in survival probabilities by revealed U-boats versus the clean control U-boats. The left-hand side shows estimates for the subsample with above-median experience commanders. The right-hand side shows estimates for below-median commanders. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

A similar picture emerges when studying commander capacity as measured in victory fixed effects. The estimated coefficients of this exercise are shown in Figure 9. I find that high-FE commanders suffer survival declines of 1.5 p.p. compared to 0.8 p.p. by low-FE commanders. Hence, in both subsample analyses, effect sizes double to triple when focussing on 'better' commanders. This suggests that the Allies predominantly used decrypts to remove high-value targets, sparing lower-value targets.

Time. Next, I investigate heterogeneity over time. This ties back to Prediction 2. In theory, the value of retaining the secret of the Enigma breach decreases toward the end of the war. Commander Kenneth Knowles (1977) provides some anecdotal evidence for a change in calculus: "We skated on some pretty thin ice in one instance later in the war when it became imperative that we gain decisive victory as soon as possible" (p. 14). The context, the sinking of several U-boats even

Figure 9: Revealing positions: U-boat survival by captain quality.



(a) Above-median fixed effects

(b) Below-median fixed effects

Notes: Figure presents event study point estimates for the differences in survival probabilities by revealed U-boats versus the clean control U-boats. The left-hand side shows estimates for above-median commanders in terms of merchant victory fixed effects. The right-hand side shows estimates for below-median commanders. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

in the absence of high-quality alternative intelligence sources.

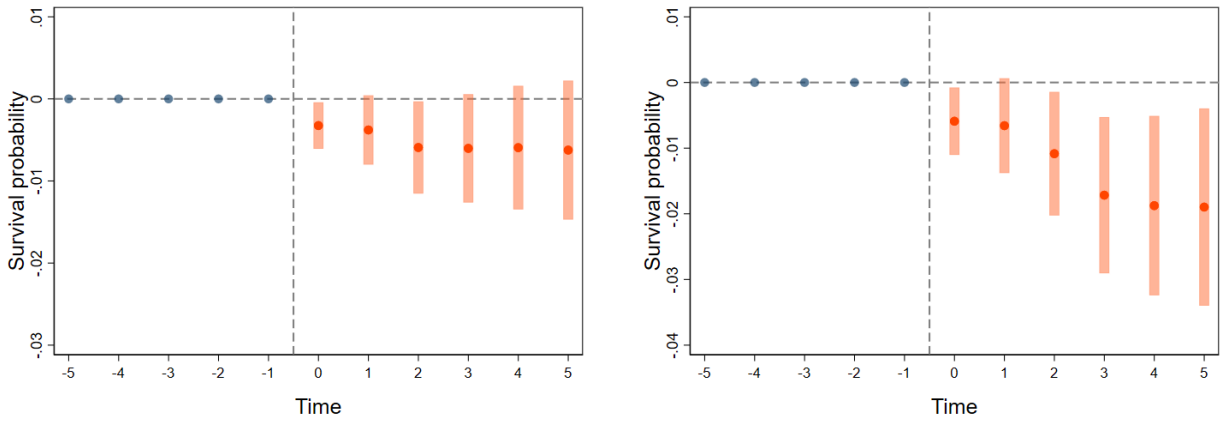
To investigate the empirical relevance of this channel, I split my sample period into two halves, 1942/43 and 1944/45, and estimate hazard rates separately. The coefficients are shown in Figure 10. Consistent with the model, I find that decrypts predict relatively small reductions in survival probability earlier in the war, but larger reductions in the final two years. Again, this is consistent with the Allies rationally varying intelligence utilization.

Operational Control. Finally, I exploit variation across different Allied partners in line with Prediction 3. One reason to expect differential effects is that the loss of Enigma intelligence loomed larger for the British than the American Allies.[37] In the data, the effect on U-boat survival should therefore be smaller in British naval zones. However, there may be other reasons outweighing any observable differences. Due to closer proximity to land-based aircraft, the British were possibly more effective in swiftly targeting U-boats.

I split the sample into American versus British designated areas. I proceed as follows. Generally,

[37] US Navy Captain Knowles (1977), for instance, opined: "[W]e Americans viewed the U-boat conflict, at least at our entry, more as a challenge than as a struggle for survival." (p. 13)

Figure 10: Revealing positions: U-boat survival earlier and later in the war.



(a) 1942-1943

(b) 1944-1945

Notes: Figure presents event study point estimates for the differences in survival probabilities by revealed U-boats versus the clean control U-boats. The left-hand side shows estimates for 1942-1943. The right-hand side shows estimates for 1944-1945. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

the US Navy was responsible for the Central and South Atlantic (Kohnen, 1999, p.119). Consistent with Barlow (2008), I code regions South of Aruba as American responsibility. However, many U-boats in the North Atlantic were also sunk by American forces. I therefore split water regions at longitude 6.31° West. I choose this longitude because it marks the Easternmost position of a U-boat sunk by American forces.[38] Conveniently, this designation splits the data set into two similarly sized samples for estimation.

The results of the split-sample regressions are shown in Figure 11. The point estimates suggest that decrypts lead to only a small, statistically insignificant, reduction in survival for U-boats in the British-designated areas. Most of the variation in the main effect is driven by American forces. This suggests that the British indeed exerted greater constraint in using Enigma intelligence compared to the Americans. Note that the same event study, but with merchant victories as outcome, is instead highly symmetrical (Appendix Figure D4). This rules out that the differences in survival rates are due to different information sets.

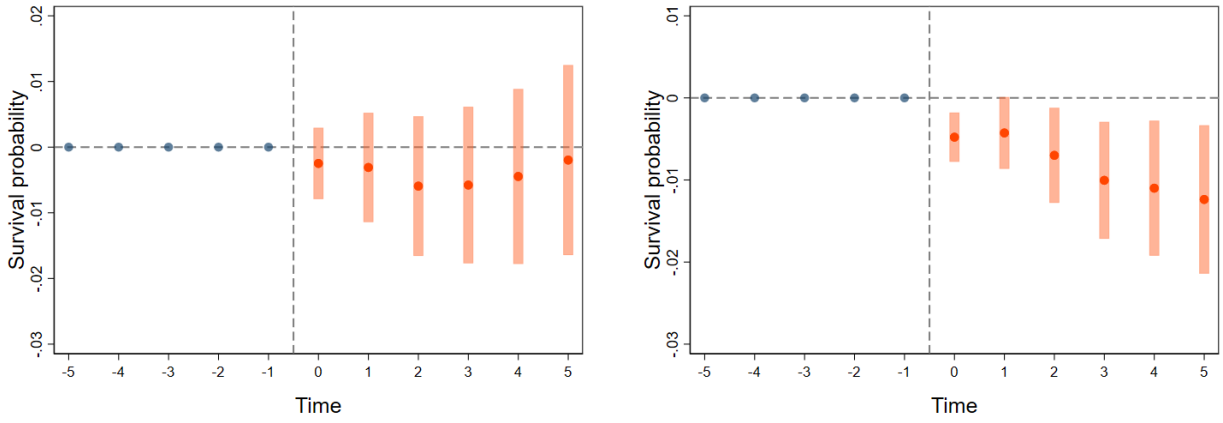
Written correspondence between American and British military leadership support the notion that

[38] See, *"U-boats Sunk by U.S. Forces with Aid of Radio Intelligence"* in Appendix I of *"OP-20-GI, Memoranda to COMINCH F21, on German U-Boat Activities, October 1943-May 1945."*, Record Group 457, National Archives, College Park, Maryland

security concerns were the main reason for these differences (Kohnen, 1999, p. 128-130). This is well-exemplified by another quote from U.S. Navy Commander Kenneth Knowles. Knowles said of his British counterpart, Rodger Winn, a senior official in the OIC:

> "Ro[d]ger had the feel of the British, naturally, of protecting ULTRA [Enigma intelligence] at all costs. So they were very cautious in utilizing ULTRA. [...] Whereas, over in my area, being younger at the game and also being somewhat aggressive we were using ULTRA more aggressively. There's quite a difference in philosophy here." (as cited in Kohnen (2019, p. 263))

Figure 11: Revealing positions: U-boat survival in different Atlantic zones.



(a) British waters

(b) American waters

Notes: Figure presents event study point estimates for the differences in survival probabilities by revealed U-boats versus control U-boats. The left-hand side shows the effect on U-boats in British-designated waters. The right-hand side shows the effect on U-boats in American-designated waters. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

Discussion. I document heterogeneity in intelligence utilization along a number of dimensions. I interpret this as consistent with a mechanism of strategic restraint. However, I recognize that some of the variation I uncover may stem from alternative mechanisms.

In particular, resource constraints could also explain some of these patterns. Under limited availability of anti-submarine units, we would equally expect the Allies to concentrate their efforts on targeting high-value U-boats. Indeed, as resource availability improved over the course of the war,

it could account for some of the increasing impact of location decrypts on U-boat losses. However, resource availability alone does not fully explain the geographic differences I uncover. Specifically, British land-based aircraft, due to their closer proximity, could have been a much more effective tool against U-boats. Yet, the empirical analysis shows minimal effects—contrary to what one would expect if resource constraints were primary drivers of heterogeneity.

In previous sections, I have already drawn on several anecdotes to support the argument that strategic restraint was top of mind among Allied leadership. To further substantiate this argument, I turn to a final piece of historical evidence focusing on a different context.

Specifically, I draw on a report by Group Captain R.H. Humphreys, a senior rank official at Bletchley Park, dating back to October 1945.[39] The report discusses disruptions to Nazi supply lines in the Mediterranean theater and reinforces several key points. First, security of the intelligence source was of utmost importance, also in this context. Humphreys states that "offensive action was NOT taken against any such shipping targets UNLESS there was clearly a second source" (p. 2), such as air reconnaissance.

Second, the report also addresses the strategic prioritization of different targets. In fact, "the information supplied permitted the establishment of an order of priority for the attack of convoys of greater or lesser importance" (p. 2). Again, this aligns closely with the heterogeneity I uncover empirically. Enigma messages primarily affected the survival probability of high-value U-boats.

Third, Humphreys alludes to differences in intelligence exploitation over time. He contents, that utilization "suffer[ed] from over-timidity in the beginning" but, interestingly, does not view missed opportunities with remorse: "because there was insufficient experience prudence could hardly be exaggerated" (p. 17).

To conclude, the dilemma of wishing to exploit Enigma intelligence while concealing its source was a persistent concern among decision-makers throughout the war. The heterogeneities observed in the data are consistent with this mechanism, as are numerous pieces of anecdotal evidence. Nonetheless, I acknowledge that my empirical analysis cannot fully disentangle variation from other possible mechanisms.

[39] "The Use of 'ULTRA' in the Mediterranean and Northwest African Theatres of War". P.R.O. AIR 40/2323, National Archives, London, Kew.

6 Quantification

In a final exercise, I ask, what was the aggregate impact of Enigma decrypts on the *Battle of the Atlantic*? To answer this question I consider two channels: (1) saving ships through rerouting and (2) the preventive sinking of U-boats to avoid future losses.

To estimate the first effect is straightforward. I combine the reduced form estimate from the U-boat efficiency loss (0.72 p.p.), the effect duration (6 days), and the number of location revelations (7443). This implies that roughly 322 ships were rerouted and saved directly from December 1942 until the end of the war.

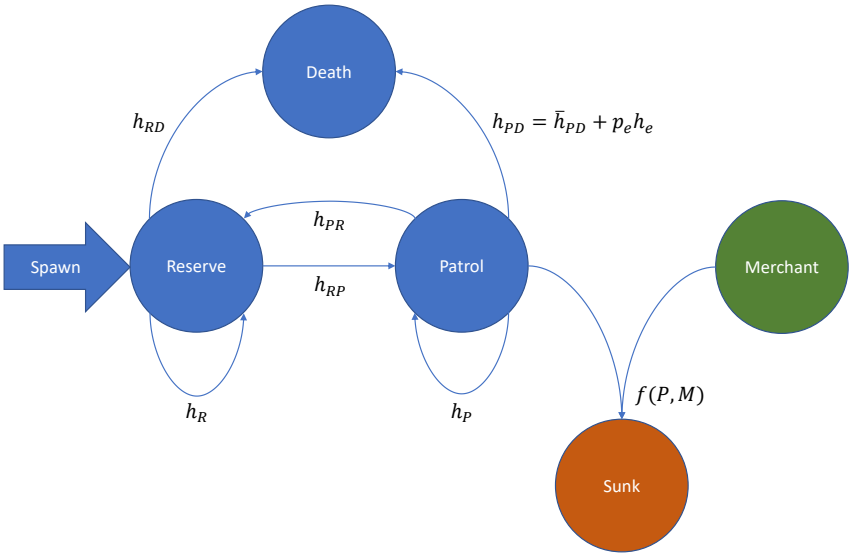
Gauging the second effect, however, is more complex. U-boats were sunk for various reasons at different times and it is unclear how long U-boats would have survived in a counterfactual world without location revelations. To address this challenge, I set up a simple simulation framework characterizing different U-boat states and flows between those states to simulate counterfactual distributions of patrolling U-boats.

The setup is as follows. New U-boats are regularly built. Once built, they are either off-duty in *reserve* (e.g., for training or repairing purposes) or they are actively on *patrol*. In both states, U-boats can *sink*. U-boats on reserve were often bombed while stationed at ports while those on patrol were sunk e.g. in combat or by accident. Flows among the states are characterized by transition rates. The key metric of interest is the number of U-boats on patrol each day, which eventually determines the number of sunk merchant ships. Figure 12 presents an overview.

To quantify the effect of saved merchant ships, I simulate counterfactual distributions of the number of patrolling units where I remove the added hazard from Enigma decrypts. From December 1942 until the end of the war, U-boats had a mean hazard rate of sinking of 0.68 p.p. every day on patrol. In the previous section, I estimated that location revelations increased the hazard rate by 1.1 p.p.[40] and that U-boats reveal their location with an 10 percent probability. Assuming a simple additive hazard rate, this implies that in a world without Enigma decrypts, U-boats would experience an average hazard rate of $0.68 - 1.1 \times 0.1 = 0.57$.

[40] While the 1.1p.p. in the reduced form exercise is the cumulative difference after five days, here I collapse it for simplicity to one day.

Figure 12: Simulation structure.

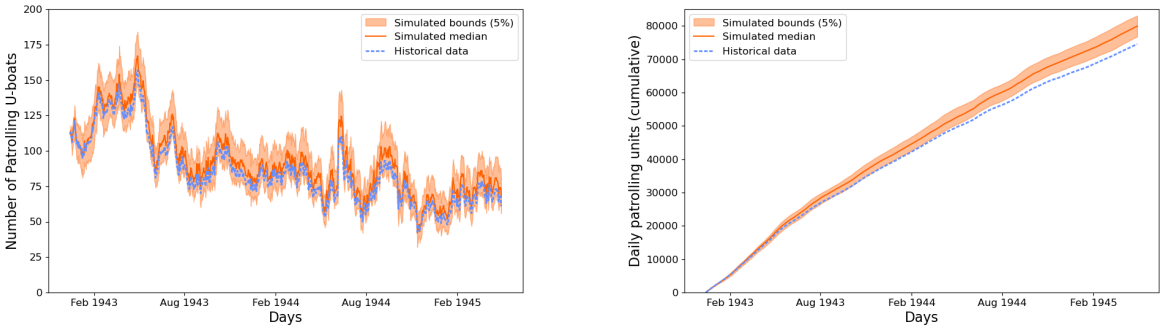


Notes: This graph characterizes the U-boat states and transition rates h.

To simulate counterfactuals, I take the empirical distribution of U-boat states in December 1942 as well as the empirical production and transition rates over the subsequent years. I then remove the added hazard rate to match the estimate in the reduced-form exercise and simulate one hundred counterfactual distributions. Figure 13 Panel (a) shows the historical number of patrolling units alongside the median and five percent bounds of the simulated counterfactuals. Interestingly, removing the added hazard rate seems to have only a small effect on the aggregate number of patrolling units. The reason is that the baseline production rate of new U-boats and the baseline hazard rates of sinking/going back to reserve are far larger than the added Enigma hazard. On average, roughly 5.4 more U-boats are on patrol every day. However, this difference becomes quantitatively meaningful when cumulated over the relevant sample period, implying about 4700 more unit-on-patrol days in the median scenario until the end of the war (Figure 13 Panel (b)).

How does this increase in unit-on-patrol days relate to merchant ship losses? I estimate a simple linear model linking the daily number of U-boats on patrols to sunk merchant ships. In the preferred specification with month-by-year and day fixed effects, one more U-boat on patrol is associated with 1.9 p.p. more merchant ships sunk per day (Table D6 Column 3). Taken together,

Figure 13: Patrolling U-boats: Empirical versus simulated distribution.



(a) Number of U-boats on patrol

(b) Cumulative U-boat-patrol days

Notes: This figure shows the results of counterfactual simulations, where I remove the estimated, added hazard from Enigma decrypts. The dashed lines indicate the historical time-series data, whereas the solid lines show the median of 100 counterfactual simulations. Light backgrounds indicate the 5 and 95 percentile bounds. The left-hand side depicts the number of patrolling U-boats per day from December 1942 - May 1945. The right-hand side shows the cumulative number of U-boats-on-patrol days.

this implies that had there been no sinkings of U-boats through Enigma decrypts, we would have expected an additional loss of 90 merchant ships.

Combining the effect of both channels, approximately 412 ships were saved, while the actual number of merchant ship losses was 601 over the relevant sample period (December 1942 until May 1945). This implies that Enigma decrypts lowered expected merchant losses by roughly 40 percent. Additionally, in this period the mean number of lives lost per ship was roughly 16. Assuming a similar rate for ships sunk in the counterfactual, I estimate that close to 6600 lives were saved through Enigma decrypts in the Atlantic.

Limitations. While the simulation, as is, provides valuable insights into the aggregate impact of Enigma decrypts, it is subject to some limitations. For instance, the framework does not explicitly account for the role of U-tankers, U-boats designed to refuel other U-boats on patrol. As discussed before, U-tankers were subject to early targeting by the Allies, because they were crucial for prolonging patrols. Kahn (1991, p. 265) estimates that with two refuels, average patrol length could essentially be doubled. In the counterfactual environment, the Allies would likely not have struck as many refuel U-boats. Transition rates from patrol to reserve would have been lower, increasing

the aggregate number of patrolling units even more. Omitting this channel, the simulation is likely to understate the true impact of Enigma intelligence.

Another key limitation is, that I do not observe aggregate merchant ship stocks and do not include it in the model. This may also introduce bias in estimating long-term merchant losses, albeit in the opposite direction. If more ships are sunk early in the sample period, fewer vessels remain available for future voyages, naturally reducing the probability of U-boats encountering and sinking merchant ships in later periods. Not accounting for this dynamic, the simulation may overstate the impact of Enigma intelligence.

However, several factors help mitigate this concern. First, the share of ships lost per voyage was generally very low. Among convoy voyages, the risk was just 0.8 p.p. across the entire war,[41] meaning that even if more ships were lost early, the overall impact on shipping stocks and long-term losses would have been relatively small. Second, greater losses would have likely prompted the Allies to ramp up ship production. Hundreds of shipping contracts were canceled before the war ended (Williams, 2014, p.17 & 46), suggesting that replacement capacity was available. Finally, I also do not uncover a significant nor quantitatively meaningful relationship between the number of voyaging ships and the number of sunk ships, once time trends are properly controlled for (Appendix Table D6 Column 3).

To conclude, the simulation does not account for all forces at play. The quantification exercise relies on the assumption that omitted factors either counterbalance one another or have limited quantitative significance. Given the arguments above, this assumption appears reasonable.

Validation. Relying on a different approach, I provide a simple validation exercise. The details are in Appendix D.1. To probe the validity of the aggregate estimate, I use a simple difference-in-differences design comparing higher-level outcomes between different Axis powers. Specifically, I focus on four months before and after December 1942, when the Allies began reading Nazi U-boat ciphers again, but no such change occurred with respect to Italian and Japanese submarines.

Compared to this control group, I find that in the subsequent months, German submarines sank

[41] 0.62 p.p. in periods of Enigma intelligence and 0.95 p.p. in periods without.

roughly 0.8 fewer merchant ships per day (Appendix Table D7). In relative terms, this corresponds to a reduction of roughly 32 percent, which broadly aligns in magnitude with the simulation result.

Counterfactuals. I perform two counterfactual experiments. First, I consider how many more ships could have potentially been saved, had the Allies struck ships with the same efficiency as in 1944/45 already in earlier periods. In this scenario, I find that 91 more ships could have been saved. Second, what would have been counterfactual outcomes, had all U-boats been sunk to the same extent as the above-median experience sample? In this scenario, 63 more ships would have survived. This suggests, that while there were some untapped gains, Enigma intelligence was already leveraged quite effectively.

Costs and Benefits. Finally, I turn to a brief economic assessment. I focus on three objects, cost of intelligence activities, merchant ship and U-boat construction.[42]

I begin by considering the cost of decryption activities. As with many other records, financial documents from Bletchley Park have only partly survived. Smith (2021) has evaluated key expenditure items covering buildings, salaries, and costs of decryption machines. He concludes that the total tally amounts to at least £12 million, or $50 million ($1.1 billion today). While this represents a lower bound (e.g. by omitting American expenditures), total cost appears to be significantly smaller than what was spent on the Manhattan Project, a staggering $2 billion ($42.7 billion today).

What were the economic gains? Consider that Enigma intelligence saved 412 merchant ships alone from December 1942 onward. A standard ship type to replace losses was the *Liberty*.[43] Average production costs are well documented, equalling roughly $1.8 million in the 1940s (Williams, 2014, p. 31) with a present value of $38 million. This implies Enigma prevented total shipbuilding cost of more than $15 *billion*.

[42] For inflation adjustment I use the Minneapolis Fed inflation calculator from 1941-2024 https://www.minneapolisfed.org/about-us/monetary-policy/inflation-calculator. For currency conversion, I rely on the FED Report *Banking and Monetary Statistics, 1914 - 1941* available at https://fraser.stlouisfed.org/title/banking-monetary-statistics-1914-1941-38/part-i-6408.

[43] For the curious reader, Liberty ship production has sparked its own small literature within economics. See Rapping (1965), Thompson (2001) and Thornton and Thompson (2001).

But this wasn't the only economic benefit. The continuous destruction of U-boats tied Nazi resources. Again, production cost data help us quantify economic losses. A standard submarine (type VII) cost roughly $1.9 million (Gröner, 1990, p. 44). Hence, the damage imposed on the Germans by the destruction of 80 U-boats through decrypts amounts to $3 billion in lost value.

Taken together, even when considering only the benefits in one specific theater of war: the return on investment from Enigma intelligence was significant.

7 Conclusion

This paper studies the role of military intelligence in conflict, focusing on the Battle of the Atlantic during World War II.

By leveraging newly digitized data on U-boat communications coupled with information on merchant vessels, I provide evidence that decrypted Enigma messages were crucial in reducing Allied shipping losses. The findings suggest that intelligence was primarily used to reroute merchant ships and, in parts, to target U-boats. This aligns with the notion of a strategic trade-off in preserving secrecy to maintain long-term informational advantages—an idea that I formalize through an asymmetric information model. Numerous pieces of anecdotal evidence and distinct heterogeneities in the data support this interpretation.

Through a combination of reduced-form analyses and a semi-structural simulation framework, I estimate that Enigma intelligence helped prevent 412 merchant ship losses from December 1942 until the end of the war—a 40 percent reduction in expected losses. These gains translated into significant economic benefits. I estimate shipbuilding cost savings of over $15 billion in present-day valuation, with damages to Nazi U-boats worth $3 billion. Additionally, Enigma intelligence prevented the loss of approximately 6,600 seamen's lives. Counterfactual exercises indicate that even more gains may have been possible, but they also highlight that the Allies exploited intelligence already extensively.

Finally, the analyses here do not address one important aspect: more efficient supply chains may have ultimately affected the length of the war. This presents itself as a promising avenue for future

research.

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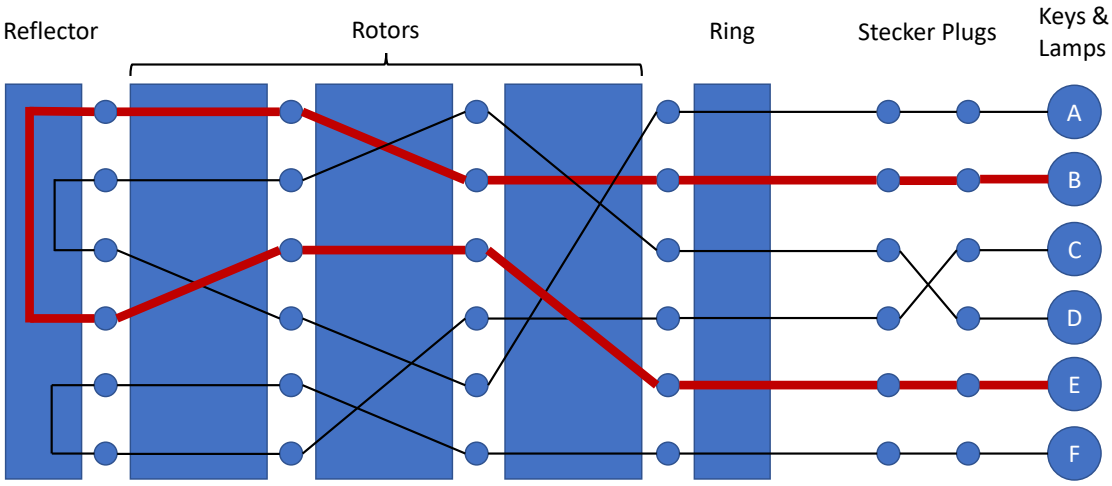
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Appendices

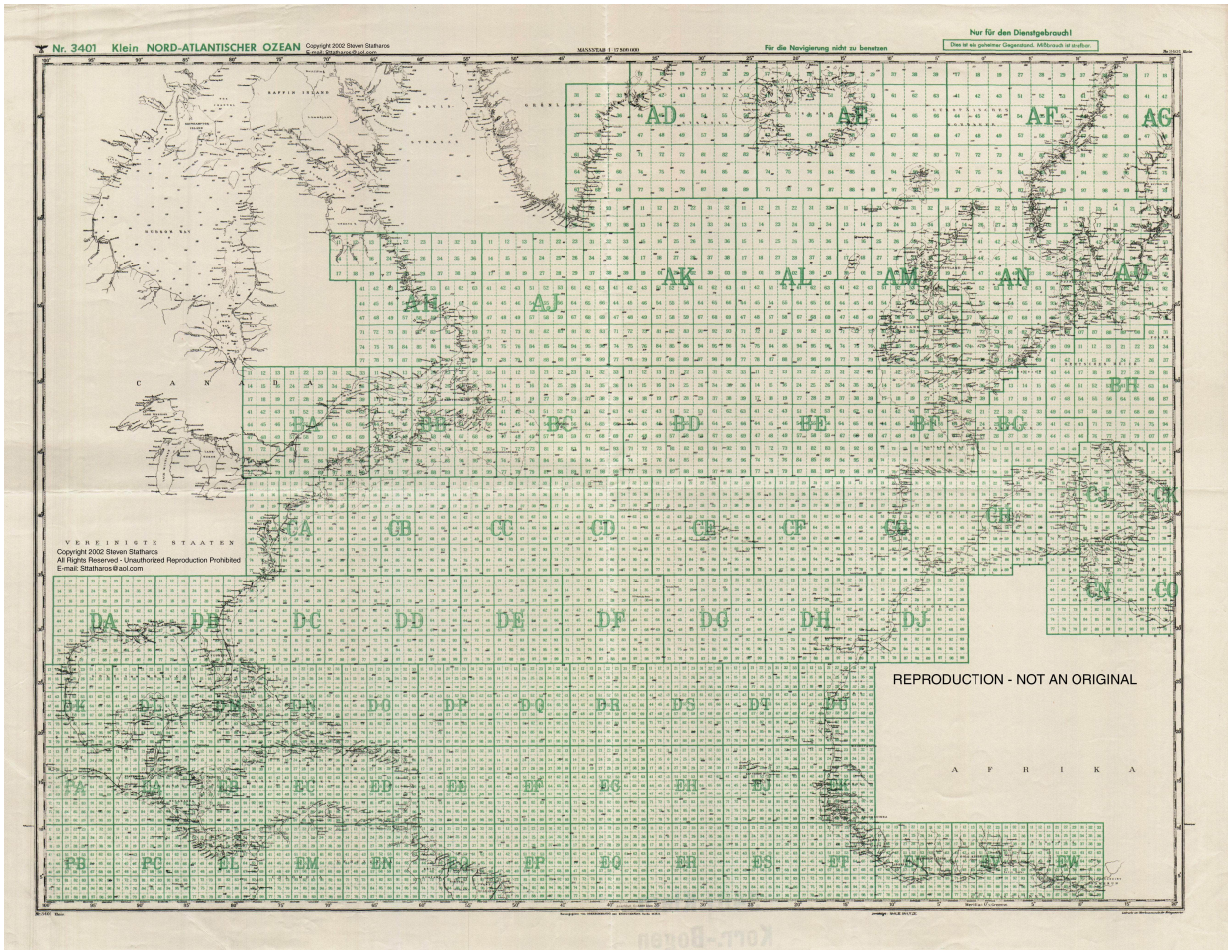
A Illustrations

Figure A1: Simplified Enigma Illustration.



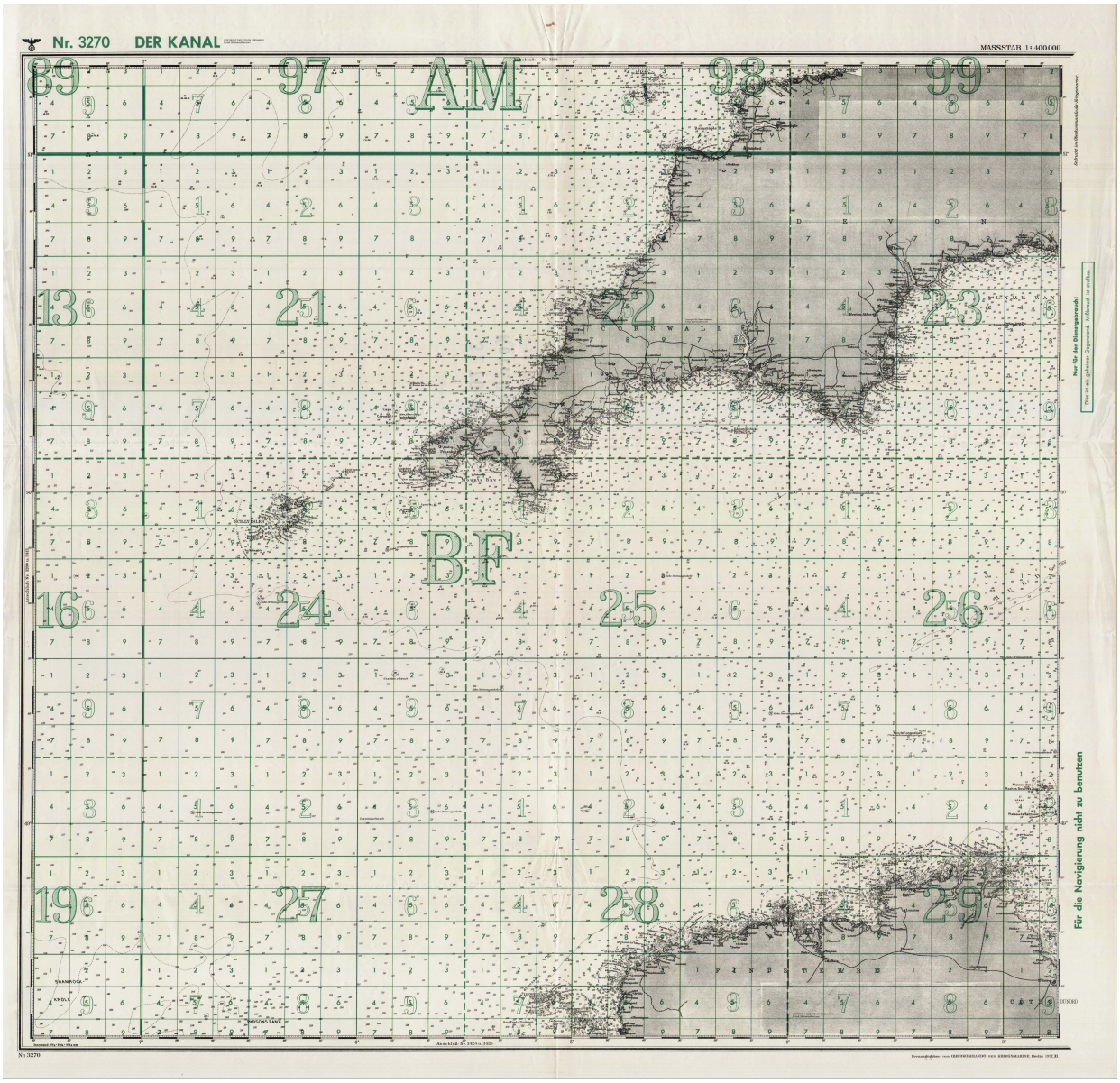
Notes: Simplified illustration of internal Enigma mechanics. Adapted from Budiansky (2000, p. 72) and Sebag-Montefiore (2000, p. 35). The operator first pressed keys in plain text. A single character would first run through the outer settings (stecker plugs), then the inner settings (ring and rotors), and back to illuminate the encoded letter lamp. After each letter, one or two rotors would advance a position at a time.

Figure A2: Grid Map North Atlantic.



Notes: Nazi grid map of the North Atlantic (broad tile structure).

Figure A3: Grid Map English Channel.



Notes: Nazi grid map of the English Channel (smallest tile structure).

B Conceptual Framework

There are two agents, the Allies and the Nazis. The Allies can be of two types, high (θ^H) or low (θ^L) capacity, where $0 < p < 1$ denotes the probability of being the high type. Essentially, we can interpret the high-type as being able to read communications while the low type cannot. Allies pursue actions s. One interpretation of s could be the number of merchant ships the Allies aim to save, or U-boats to sink. However, actions are associated with type-dependent costs. Both high- and low-type could theoretically save/sink the same number of ships/U-boats, but the associated costs differ. More precisely, flow utility is described by

$$U_A(s) = s - \frac{1}{2\theta^i}s^2.$$

In a one-period setup, Allies would optimize choosing $s^i = \theta^i$. Assuming $\theta^H > \theta^L$, the high type chooses a higher level of s.

While the Allies choose s ships to save/U-boats to sink, the actual realization is is subject to noise. Nazi's only observe the realization z:

$$z = s + \tilde{\varepsilon}$$

where $\tilde{\varepsilon}$ is drawn from a uniform distribution with boundaries $[-\varepsilon/2, \varepsilon/2]$. I further assume that the noise is relatively large, i.e. $\varepsilon > \theta^H - \theta^L$.

There are two periods. First, Allies are assigned their type and determine an action level s_1 in period 1. Then, Nazis observe z (where I omit the subscript for convenience). Before period 2, the Nazis can either invest in a security upgrade at a fixed cost c or not. The upgrade can essentially be viewed as a new encryption system. If they undertake the investment, Allies attain the low-type cost structure in the second period regardless of their type. If they do not invest, Allies keep their initial cost structure. After the publicly known investment decision, Allies optimize flow utility as before. Period 2 utility is, however, discounted at factor β from the point of view of period 1. The Nazi payoff in period 2 is

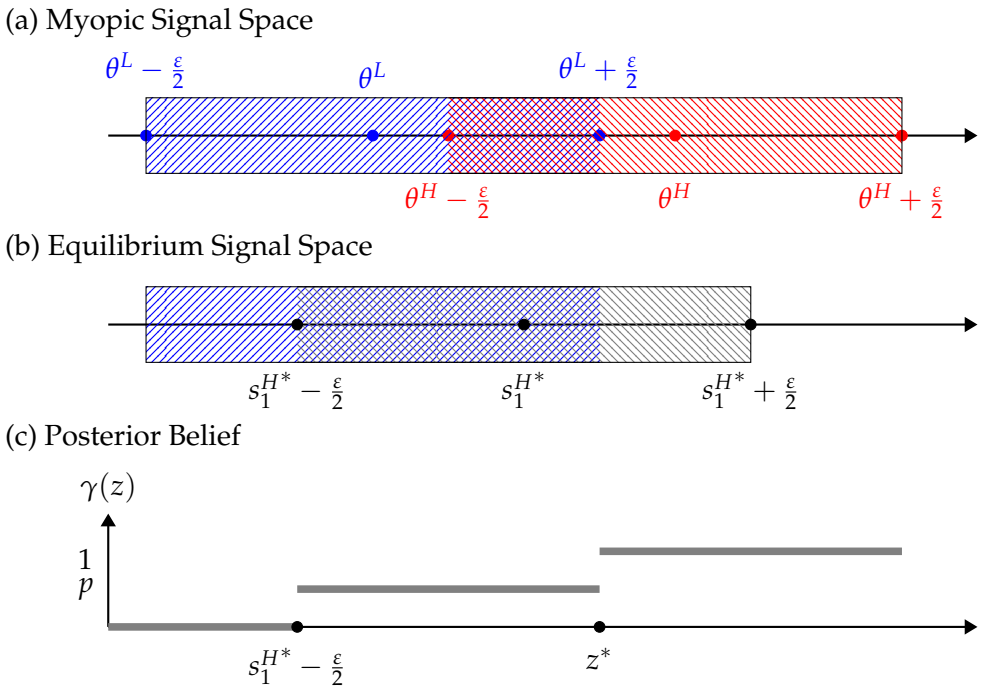
$$U_N(c) = -s_2 - c,$$

while first-period pay-off doesn't matter.

I define an equilibrium as a set of strategies by Allies and Nazis that represent best-responses to each other and beliefs by Nazis that map all signals to a Bayesion posterior about the Allied type.

An equilibrium consistent with the historical record is described by the following conjectures and decision rules. The Nazi's adopt a cutoff rule, in which they engage in costly upgrading only if the observed noisy action-level is beyond a threshold level $z^* = \theta^L + \frac{\varepsilon}{2}$. The low-type Allies confirm to $s^{L*} = \theta^L$ in both periods. Assuming a parameterization consistent with an interior solution, the high-type will instead choose a level $s_1^{H*} = \theta^H \left[1 - \beta \frac{\theta^H - \theta^L}{\varepsilon} \frac{1}{2}\right] < \theta^H$ in the first period. This essentially captures the idea of under-utilization of intelligence capacity. Absent the security investment, they choose $s_2^{H*} = \theta^H$ in the second period, or, else, $s_2^{H*} = \theta^L$.

Illustration



Derivations. Let the Nazi's upgrade according to a threshold rule. The probability of *avoiding* an upgrade is then,

$$F(z^* - s_1) = \begin{cases} 0, & z^* - s_1 < -\frac{\varepsilon}{2}, \\ \frac{1}{\varepsilon}(z^* - s_1 + \frac{\varepsilon}{2}), & -\frac{\varepsilon}{2} \leq z^* - s_1 \leq \frac{\varepsilon}{2}, \\ 1, & z^* - s_1 > \frac{\varepsilon}{2}. \end{cases}$$

Consider the high type before period 2. If the Allies retain their cost structure, they will receive payoff $\frac{1}{2}\theta^H$, and $\frac{1}{2}\theta^L$, if upgrading is triggered. In period 1, high-type Allies therefore maximize

$$\max_{s_1} \left\{ \underbrace{s_1 - \frac{1}{2\theta^H} s_1^2}_{\text{first period}} + \beta \underbrace{[F(z^* - s_1)]}_{\text{prob. staying H}} \underbrace{0.5\left(\theta^H - \theta^L\right)}_{\text{benefit of staying H}} \right\}$$

Assuming a parameterization consistent with an interior solution, optimization yields

$$s_1^{H*} = \theta^H \left[1 - \beta \frac{\theta^H - \theta^L}{\varepsilon} \frac{1}{2}\right],$$

which is smaller than θ^H and is conveniently independent of z^*.

Next, we turn to the Nazis. Suppose the Nazis correctly conjecture that the Allies optimally choose s_1 in both states of the world. What is their optimal cutoff value z^*? Given strategy s_1^{H*}, the belief of the Allies being the high type is determined by Bayes,

$$\gamma(z) = \begin{cases} 0, & z < s_1^{H*} - \frac{\varepsilon}{2}, \\ p, & s_1^{H*} - \frac{\varepsilon}{2} \leq z \leq \theta^L + \frac{\varepsilon}{2}, \\ 1, & z > \theta^L + \frac{\varepsilon}{2}. \end{cases}$$

There are two candidate solutions

$$z^* \in \left\{ s_1^{H*} - \frac{\varepsilon}{2}, \theta^L + \frac{\varepsilon}{2} \right\}.$$

Suppose that $z^* = s_1^{H^*} - \frac{\varepsilon}{2}$ is optimal. This implies that the high-type Allies will always face a security upgrade, despite choosing a lower s_1 than the myopic optimum. The high-type is therefore better off deviating and this cannot constitute an equilibrium.

We remain with $z^* = \theta^L + \frac{\varepsilon}{2}$. For this to be optimal, it must not be cost-effective to invest in the security upgrade, when the posterior equals p. This requires the following condition:

$$\underbrace{p(-\theta^H) + (1-p)(-\theta^L)}_{\text{expected payoff without upgrade}} > \underbrace{-\theta^L - c}_{\text{payoff with upgrade}}$$

$$p < \frac{c}{\theta^H - \theta^L}.$$

But it needs to be worth investing, when the posterior equals 1,

$$-\theta^H \leq -\theta^L - c$$

$$c \leq \theta^H - \theta^L.$$

Assumptions (overview).

- $\theta^H > \theta^L$,
- $\tilde{\varepsilon} \sim \mathcal{U}\left(-\frac{\varepsilon}{2}, \frac{\varepsilon}{2}\right)$,
- $\varepsilon > \theta^H - \theta^L$,
- $\theta^L < s_1^{H^*} = \theta^H \left[1 - \beta^{\frac{\theta^H - \theta^L}{\varepsilon}} \frac{1}{2}\right]$,
- $p(\theta^H - \theta^L) < c \leq \theta^H - \theta^L$.

Predictions. First, I define restraint as the wedge between $s_1^{H^*}$ and the myopic optimum θ^H.

1. Restraint decreases in noise. Consider rerouting merchant ships and sinking U-boats separately. Nazis are fully aware of their U-boats, their states, positions etc. while having an accurate sense of how many merchant ships there are and how many ought to sink is much more opaque. In the model, we can characterize this as different levels of noise ε (while remaining within the confines of an interior solution). Comparative statics reveal:

$$\frac{\partial s_1^{H^*}}{\partial \varepsilon} = \frac{1}{2} \frac{\theta^H \beta (\theta^H - \theta^L)}{\varepsilon^2} > 0.$$

When noise increases, so does s_1^{H*}. This implies with greater noise, we expect under-utilization to decline. Mapping this to the data, we should observe less restraint in terms of rerouting merchant ships, but greater restraint with respect to sinking U-boats.

2. Restraint decreases over time. Consider β as a relative weight of the future. The weight is larger if the second period is expected to be longer and smaller vice versa. Comparative statics reveal:

$$\frac{\partial s_1^{H*}}{\partial \beta} = -\frac{1}{2}\frac{\theta^H(\theta^H - \theta^L)}{\varepsilon} < 0.$$

When the future period has greater weight (earlier in the war) we would expect a smaller s_1^{H*} – a higher degree of underutilization. The closer we approach the end, the smaller becomes β. Under-utilization declines.

3. Restraint increases in the relative value of retaining/losing Enigma intelligence. Consider an extended version of the model. Let flow utility be

$$U_A(s) = \gamma s - \frac{1}{2\theta^i}s^2,$$

where the addition of $\gamma > 0$ can be interpreted as a value shifter for additionally saved ships/ sunk submarines. The mypoic optimum then becomes $s^{i*} = \gamma\theta^i$ and the benefit of retaining the high-type cost structure in the final period therefore $\frac{1}{2}\gamma^2[\theta^H - \theta^L]$. Increasing γ makes revealing the high type more costly in relative terms.

The empirical analogy is the differences in intelligence value between British and American forces. For the UK, disruptions to the Atlantic supply line loomed plausibly larger than for the US. Normalizing $\gamma_1 = 1$ in the first period, comparative statics yield:

$$\frac{\partial s_1^{H*}}{\partial \gamma_2} = -\beta\gamma_2\theta^H\frac{(\theta^H - \theta^L)}{\varepsilon} < 0.$$

This implies that higher relative valuations of losing Enigma intelligence increase the willingness to forgo benefits in the first period. We would expect the UK to exert more constraint in utilizing

intelligence.

C Data construction

C.1 Assigning vessels to the Shark network.

Data on sunk convoys were collected from https://uboat.net/ops/convoys/convoys.php. Based on the position of the loss, I assign convoys to the Shark U-boat network.[44] From the beginning of the war until February 1942, all U-boats were jointly on one communication network, the Dolphin network. After February 1942, all U-boats then transitioned to the Shark network, except those that were stationed in the Far North (Hinsley, 1984, Appendix 3). Beginning in June 1943, U-boats in the Mediterranean exited Shark and entered the Turtle network (Hinsley, 1984, Appendix 3). I exclude respective convoys from the time series. In October 1943, U-boats in the Black Sea migrated to the Grampus network and in February 1945, U-boats in the Far East entered Sunfish (Erskine and Marks, 2004). As before, I only keep convoys that were passaging through waters in which U-boats continued to communicate on the Shark network. Toward the end of the war, this mainly consisted of convoys in the Atlantic.

C.2 Sources

I collect data from a variety of sources.

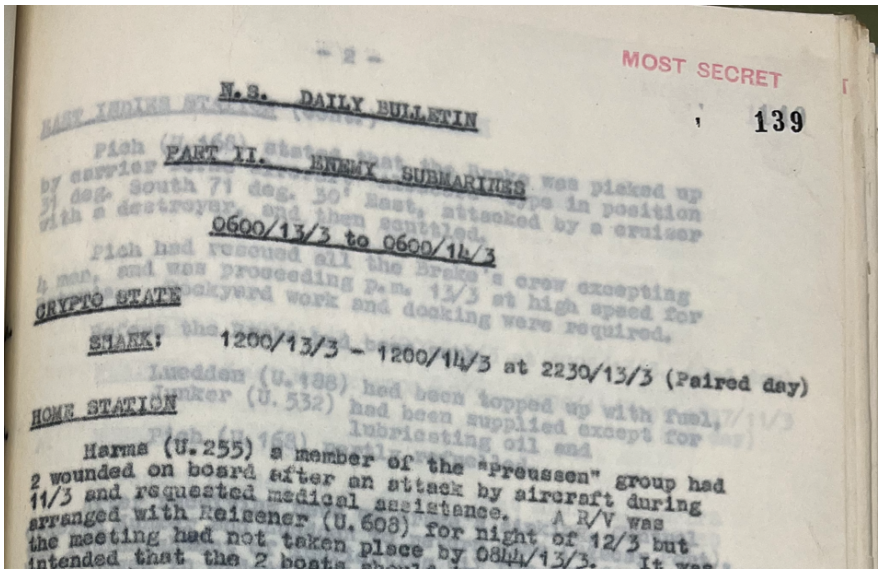
Table C1: Data sources

Data	**Source**
Merchant ships hit by German Submarines	Uboat.net
Merchant ships hit by Italian Submarines	Uboat.net
Merchant ships hit by Japanese Submarines	Rohwer (1999)
Sunk German Submarines	Uboat.net
Sunk Italian Submarines	Uboat.net
Sunk Japanese Submarines	Naval History Division (1963) [2017]
Key breaking speed	Naval Section: Daily Bulletins (National Archives, Kew: HW 8/2)
Decrypts	Teleprinted Translations of Decrypted German U-Boat Traffic. December 1942-December 1945 (National Archives, Kew: DEFE 3/705-744)

[44] To map sunk convoys I use global oceans and seas shape files from the Flanders Marine Institute (2018, 2021).

C.3 Key-breaking speed

Figure C1: Example: daily breaking time.



MOST SECRET

139

N.S. DAILY BULLETIN

PART II. ENEMY SUBMARINES

0600/13/3 to 0600/14/3

CRYPTO STATE

SHARK: 1200/13/3 - 1200/14/3 at 2230/13/3 (Paired day)

HOME STATION

Harma (U.255) a member of the "Preussen" group had 2 wounded on board after an attack by aircraft during 11/3 and requested medical assistance. A R/V was arranged with Reissener (U.608) for night of 12/3 but the meeting had not taken place by 0844/13/3.

Notes: Excerpt from the N.S. Daily Bulletin documenting when the Shark key for the 13th of March 1944 (to 14th) was broken (National Archives, Kew: HW 8/2).

C.4 Decrypts

Data processing. First, I collected all decrypt scans (n=43272) held at the National Archives, Kew. These are readily available online and can be downloaded after registration. Next, I used a random sample of 865 scans to classify picture segments using Roboflow. Segment classes were for instance "time of intercept" and "time of relay" (to the OIC). These data were then split into training (n=605), validation (n=174), and test (n=81) data sets. Next, I trained a segmentation model relying on the Detectron2 library (Wu et al., 2019) on Google Colab. After segmenting the original scans, I used Google Vision Control to extract the relevant text information from the picture segments.

To identify specified U-boats, I first created lists of patrolling U-boats/ commanders for each day over the analysis period (allowing for +2/-2 week deviations). I then employed a fuzzy-string search of commander names in the decrypts, as well as U-boat numbers. To identify decrypts with and without specific location information I created a dummy recording unity if a decrypt mentioned "position", "square" or "degree". Prior manual inspection of decrypts revealed that grid point information was almost always accompanied by one of these terms. This approach avoids incorrectly recording random OCR output as grid point coordinates. Finally, for time information, I extracted the "time of relay" and the "time of intercept" using Regex. Time of relay captures when decrypts were sent to the OIC (British time zone), essentially when they became operationally valuable. The time of intercept denotes when the encrypted text was received at radar stations (British time zone). Some decrypts also include a time of origin, denoting the signal origin in German time. Typically the time of origin and time of intercept were within the same hour. Thus, in case of missing intercept time, I impute using the time of origin.

For validation, I cross-checked the algorithmic output with a random sample of 100 manually coded decrypts.

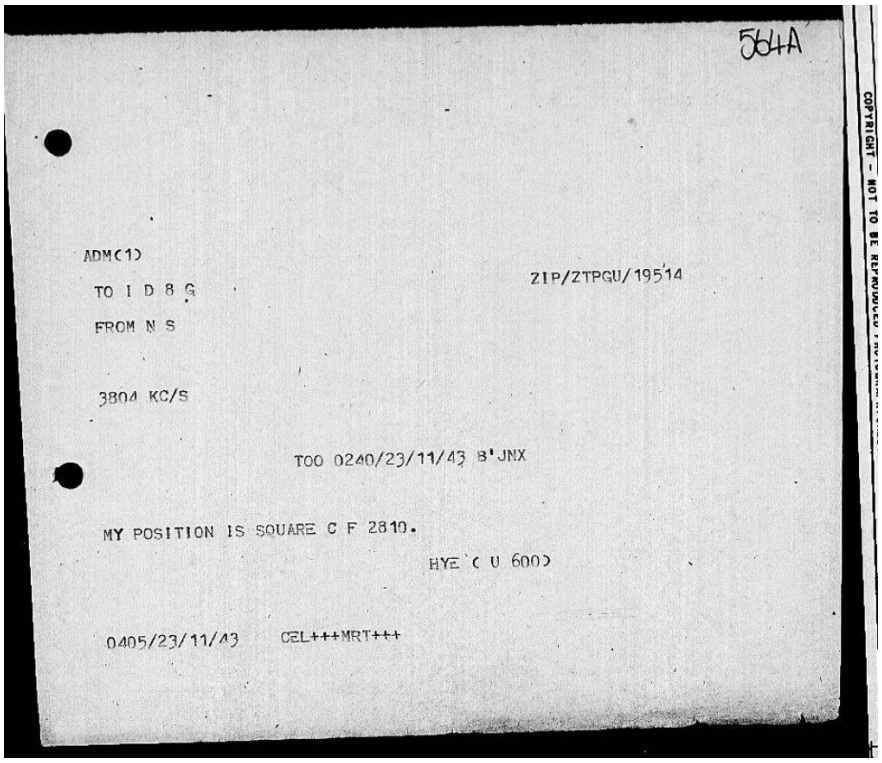
- U-boats
  - Manually: identified 94 U-boats
  - Algorithm: 82 correctly identified, 6 false entries, 12 missing
- Position revelations
  - Manually: 47 identified position reports

  - Algorithm: 42 correctly identified, 0 false entries, 5 missing
- Time of relay
  - Manually: 92 identified time reports
  - Algorithm: 82 correctly identified, 0 false entries, 10 missing
- Time of intercept
  - Manually: 96 identified time reports
  - Algorithm: 91 correctly identified, 1 false entry, 4 missing

To provide some intuition for errors in data processing, among the 6 false positives in U-boats, 4 were related to Josef *Will*. The string "will" appeared in four messages as a verb. All missing position reports stem from position reports that did not relate to Reichsmarine grid points, but instead to longitude/latitude coordinates. Missings in the time of relay/intercept stem broadly from segmentation and OCR errors. The few OCR errors occur mainly due to poor scan quality and (hand-written) corrections overwriting machine-typed text.

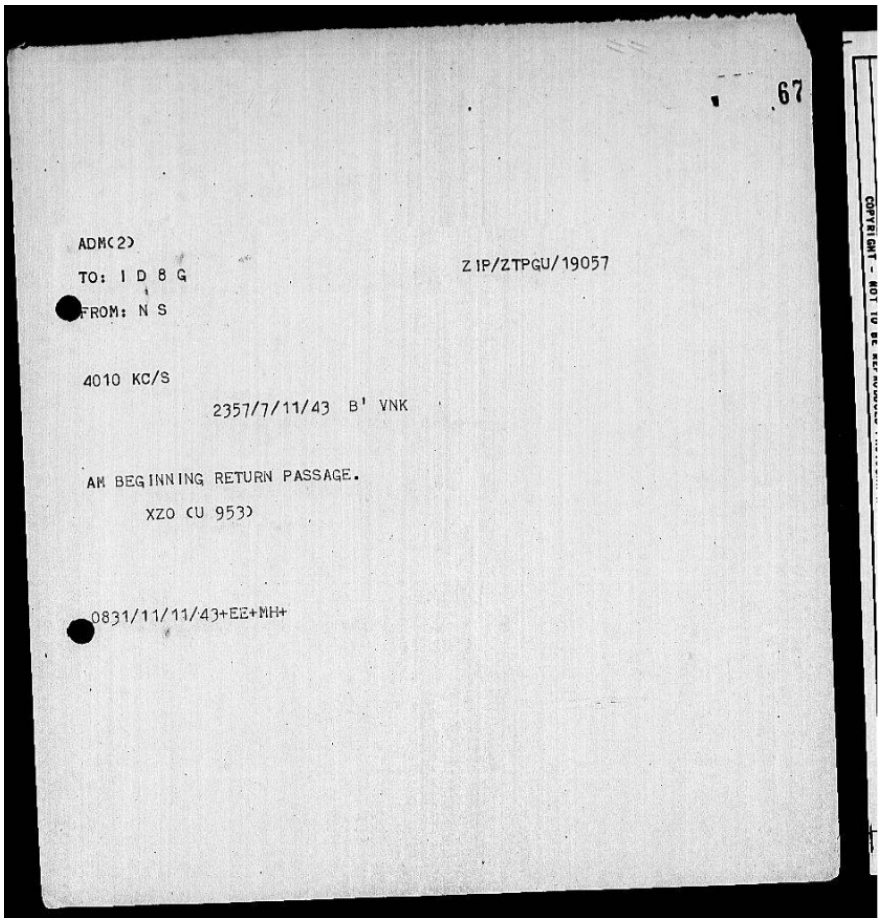
Examples. Two examples of decrypt scans are provided below.

Figure C2: Example: Decrypt I.



Notes: Decrypts (National Archives, Kew: DEFE 3/724).

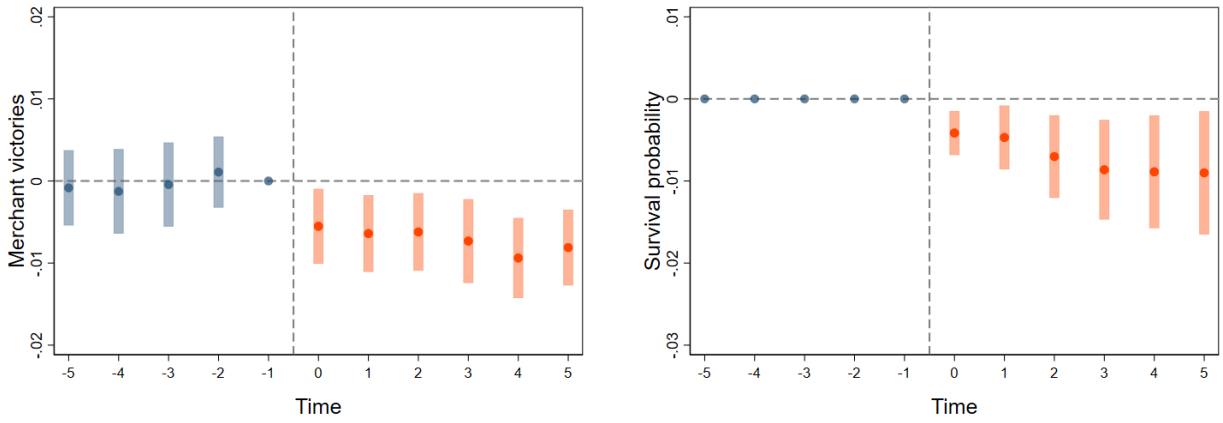
Figure C3: Example: Decrypt II.



Notes: Decrypts (National Archives, Kew: DEFE 3/724).

D Further results and robustness

Figure D1: Revealing positions: messages without co-mentioning "convoy".

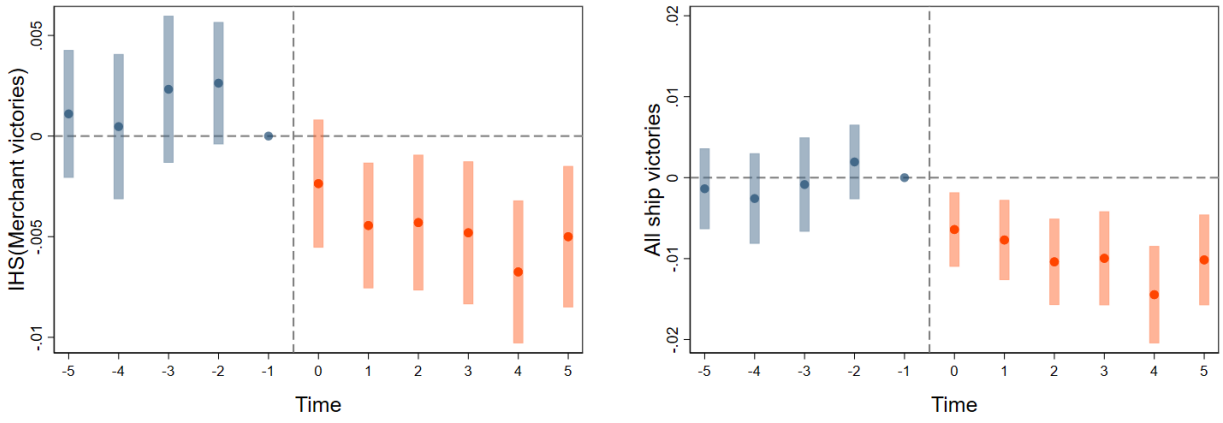


(a) Sunk merchant ships

(b) U-boat survival

Notes: Left-hand figure presents event study point estimates for the differences in victories over merchant vessels by revealed U-boats versus the clean control U-boats. Right-hand figure presents survival probabilities. Treatment of interest are decrypts with location information that do not co-mention "convoy". Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

Figure D2: Revealing positions: robustness to different measurements of Allied shipping losses.

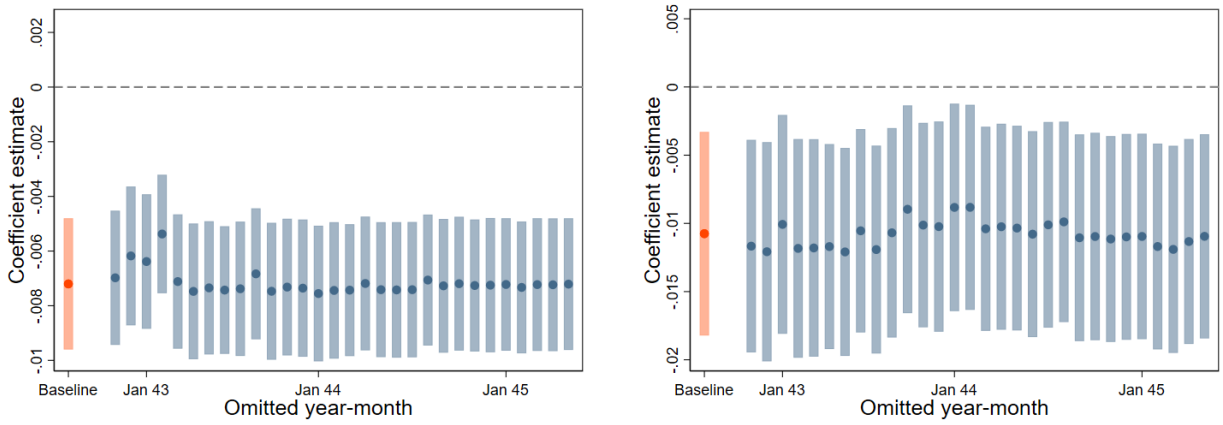


(a) IHS of sunk merchant ships

(b) Sunk merchant ships and battleships

Notes: Left-hand figure presents event study point estimates using the inverse hyperbolic sine of victories over merchant vessels as outcome. Right-hand figure presents event study coefficients for the effect on all victories, including battleships. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

Figure D3: Revealing positions: outlier sensitivity.

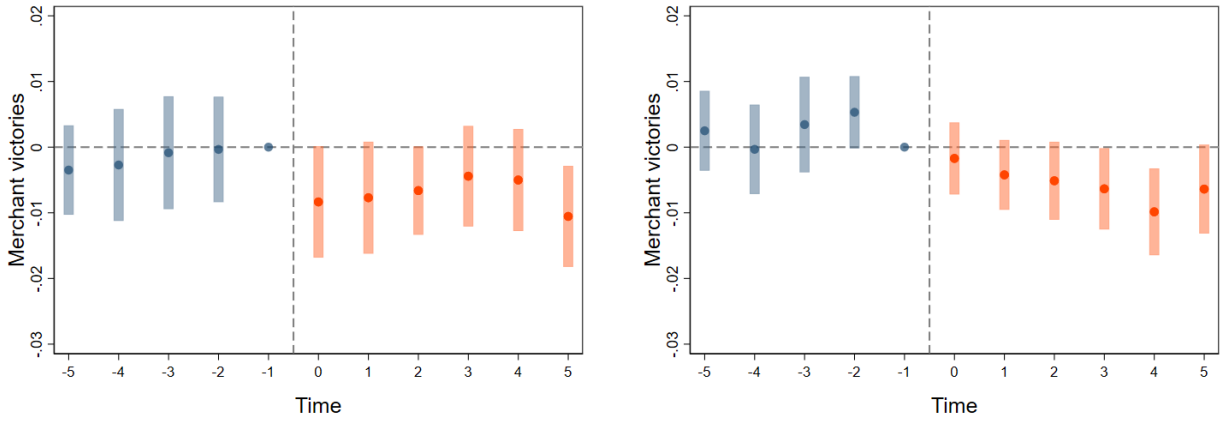


(a) Sunk merchant ships

(b) U-boat survival

Notes: I estimate coefficients on different subsamples, iteratively omitting U-boat cohorts from different year-months. Left-hand figure presents average treatment effects on victories over merchant ships before and after U-boats reveal locations. Right-hand figure presents survival probabilities five days after treatment occured. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

Figure D4: Revealing positions: merchant victories in different Atlantic zones.



(a) British waters

(b) American waters

Notes: Figure presents event study point estimates for the differences in victories over merchant vessels by revealed U-boats versus the clean control U-boats. The left-hand figure shows the effect on merchant losses in British-designated waters. The right-hand figure shows the effect on merchant losses in American-designated waters. Lines indicate 95 percent confidence intervals. Standard errors are clustered on U-boat-level.

Table D1: Two day cycle in key-breaking speed.

	Time to break			IHS(Time to break)		
	(1)	(2)	(3)	(4)	(5)	(6)
Paired settings	-8.268***	-8.246***	-8.137***	-0.270***	-0.268***	-0.265***
	[2.288]	[2.024]	[1.974]	[0.087]	[0.066]	[0.065]
Day FE	No	Yes	Yes	No	Yes	Yes
Month FE	No	Yes	No	No	Yes	No
Year FE	No	Yes	No	No	Yes	No
Year-Month FE	No	No	Yes	No	No	Yes
R^2	0.024	0.266	0.307	0.018	0.452	0.471
Mean dep var	30.276	30.276	30.276	3.735	3.735	3.735
Observations	522	522	522	522	522	522

Notes: Unit of observation: day. Paired settings is a dummy variable attaining one on even calendar days. Time to break refers to the number of hours until daily Shark settings were identified. IHS is the inverse hyperbolic sine transformation of this value. Sample period November 1943 to May 1945. Robust standard errors.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table D2: Two day cycle in decryption of messages.

	$\mathbb{1}$(Relayed within 12h)			IHS(Relay time)		
	(1)	(2)	(3)	(4)	(5)	(6)
Paired settings	0.059**	0.057***	0.058***	-0.234**	-0.222***	-0.224***
	[0.026]	[0.022]	[0.020]	[0.100]	[0.084]	[0.076]
Day FE	No	Yes	Yes	No	Yes	Yes
Month FE	No	Yes	No	No	Yes	No
Year FE	No	Yes	No	No	Yes	No
Year-Month FE	No	No	Yes	No	No	Yes
R^2	0.005	0.136	0.213	0.006	0.216	0.336
Mean dep var	0.261	0.261	0.261	4.155	4.155	4.155
N Clusters	860	860	860	860	860	860
Observations	30922	30922	30922	30922	30922	30922

Notes: Unit of observation: decrypt. Paired settings is a dummy variable attaining one if the message was intercepted on even calendar days. Relay time refers to the difference in hours between interception and transmission to the OIC. I show correlations with a dummy for 'relayed within 12h' and with the inverse hyperbolic sine of the relay time. Sample covers messages intercepted between December 1942 to May 1945. Standard errors clustered by date.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table D3: Two day cycle in outcomes.

	Sunk merchant ships			Sunk U-boats		
	(1)	(2)	(3)	(4)	(5)	(6)
Paired settings	-0.171*	-0.170*	-0.171**	0.043	0.045	0.046
	[0.095]	[0.089]	[0.085]	[0.051]	[0.049]	[0.048]
Day FE	No	Yes	Yes	No	Yes	Yes
Month FE	No	Yes	No	No	Yes	No
Year FE	No	Yes	No	No	Yes	No
Year-Month FE	No	No	Yes	No	No	Yes
R^2	0.003	0.149	0.237	0.001	0.104	0.157
Mean dep var	0.746	0.746	0.746	0.446	0.446	0.446
Observations	1060	1060	1060	1060	1060	1060

Notes: Unit of observation: day. Paired settings is a dummy variable attaining one on even calendar days. Outcomes are the number of sunk Allied merchant ships and Nazi U-boats. Sample covers the periods in which U-boat Enigma codes were broken: August 1941 to January 1942 and December 1942 to May 1945. Robust standard errors.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table D4: Placebo test: two day cycle in outcomes.

	Sunk merchant ships			Sunk U-boats		
	(1)	(2)	(3)	(4)	(5)	(6)
Paired settings	-0.114	-0.117	-0.117	0.014	0.014	0.015
	[0.129]	[0.118]	[0.115]	[0.025]	[0.024]	[0.024]
Day FE	No	Yes	Yes	No	Yes	Yes
Month FE	No	Yes	No	No	Yes	No
Year FE	No	Yes	No	No	Yes	No
Year-Month FE	No	No	Yes	No	No	Yes
R^2	0.001	0.177	0.224	0.000	0.062	0.100
Mean dep var	1.821	1.821	1.821	0.115	0.115	0.115
Observations	1014	1014	1014	1014	1014	1014

Notes: Unit of observation: day. Paired settings is a dummy variable attaining one on even calendar days. Outcomes are the number of sunk Allied merchant ships and Nazi U-boats. Sample covers the periods in which U-boat Enigma codes were *not* broken: September 1939 to July 1941 and February 1942 to December 1942. Robust standard errors.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table D5: Average treatment effects

	Baseline	- Conv. mentioned	IHS	+ Battleships
	(1)	(2)	(3)	(4)
Location revealed	-0.720***	-0.687***	-0.032***	-0.928***
	[0.123]	[0.130]	[0.005]	[0.149]
h-U-boat FE	Yes	Yes	Yes	Yes
h-day FE	Yes	Yes	Yes	Yes
R^2	0.126	0.126	0.129	0.128
Mean dep var	0.785	0.782	0.035	1.123
Observations	474375	472758	474375	474375

Notes: Unit of observation: U-boat day. Outcome is the number of ships sunk multiplied by 100, so magnitudes can be interpreted as percentage points. Column 1 is the baseline difference-in-differences regression to equation 2. Column 2 shows the estimate for location decrypts, that do not co-mention "convoy". Column 3 shows the baseline effect on the inverse hyperbolic sine of the number of sunk ships. Column 4 adds the number of sunk battleships to the outcome variable. Standard errors are clustered on U-boat-level.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table D6: Correlation between patrolling units and sunk merchant ships.

	Sunk merchant ships			
	(1)	(2)	(3)	(4)
U-boats on patrol	0.015***	0.014***	0.019***	0.045***
	[0.002]	[0.003]	[0.006]	[0.013]
Ships on voyage (1000s)	-2.941***	-0.958***	0.148	0.274
	[0.149]	[0.365]	[0.497]	[1.155]
Day FE	No	Yes	Yes	Yes
Month FE	No	Yes	No	No
Year FE	No	Yes	No	No
Year-Month FE	No	No	Yes	Yes
R^2	0.136	0.214	0.291	0.232
Mean dep var	1.271	1.271	1.271	1.821
Sample	Full	Full	Full	No Enigma
Observations	2074	2074	2074	1014

Notes: Unit of observation: day. U-boats on patrol is the daily number of patrolling U-boats. Ships on voyage are the number of merchant vessels actively sailing in covoys in units of 1000s. Sample periods either September 1939 to May 1945 if "Full" indicated, or if "No Enigma" indicated, the periods in which U-boat Enigma codes were *not* broken: September 1939 to July 1941 and February 1942 to December 1942. Robust standard errors.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

D.1 Validation

To perform a simple validation exercise, I study differences in aggregate outcomes across different Axis powers focusing on the change in the information environment in December 1942. Empirically, I employ a canonical difference-in-differences design. The first difference is time, where I compare periods before and after the 14th of December 1942 when the Allies relearned how to read Enigma messages. The second difference I rely on are successes and losses by other Axis powers engaged in U-boat warfare, the Japanese and Italians. Importantly, the treatment status of the control groups did not switch around the event period. Italian submarines typically operated in radio silence, having been instructed before patrols. Hence, there was less scope to engage in decryption (Chadwick, 2011).[45] Japanese naval ciphers were instead regularly read starting from the 18th of March 1942 (Budiansky, 2000, p. 342). I then estimate the following equation

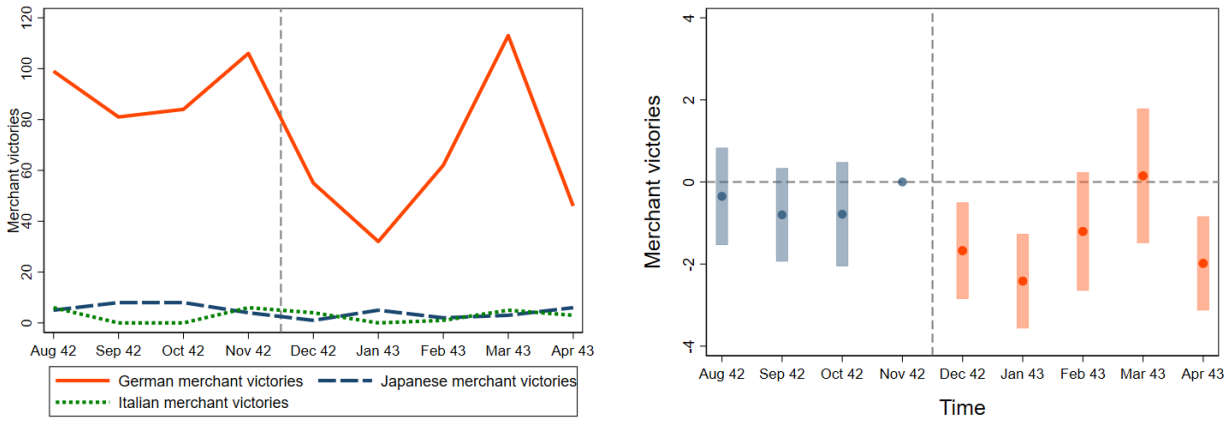
$$y_{it} = \beta Post_t \cdot Nazi_i + \alpha_i + \gamma_t + \varepsilon_t \tag{4}$$

where y_{it} are conflict outcomes on day t for Axis power i, $Post_t$ is an indicator that equals one for days after the 14th December 1942, $Nazi_i$ is an indicator for Nazi war outcomes. α_i capture Axis power fixed effects, since Germans sunk many more convoys than the Japanese and Italians. Finally, γ_t are year-month fixed effects, and ε_t denotes the error term. Standard errors are clustered by date.

The corresponding event study estimates, binned by month to reduce noise, are shown in Figure D5. I find that roughly 0.8 fewer merchant ships per day are being sunk in the post-period (Appendix Table D7). This corresponds to a reduction of roughly 32 percent. I interpret the similarity in magnitude relative to the simulation result as evidence supporting the credibility of the quantification exercise.

[45] One disadvantage of this approach was that when an Italian submarine was captured, documents on board revealed patrolling orders of other submarines. For instance, the capture of the *Galileo Galilei* led to three subsequent submarine losses (Hinsley, 1979, p. 209).

Figure D5: Reading Enigma ciphers: zooming in on the 14th December 1942.



(a) Sunk merchant vessels (raw data)

(b) Sunk merchant vessels (event study)

Notes: The left-hand figure presents the number of sunk convoys per month and Axis power. The right-hand figure presents event study point estimates for the differences in merchant ships sunk by Germans versus Japanese and Italians. Lines indicate 95 percent confidence intervals. Standard errors are clustered by date.

Table D7: Static difference-in-differences: Effect on hit merchant vessels.

	Sunk merchant ships	
	(1)	(2)
German × Post	-0.796***	-0.796***
	[0.306]	[0.306]
German	2.763***	
	[0.189]	
Post	-0.050*	
	[0.028]	
Axis power FE	No	Yes
Date FE	No	Yes
Cons.	Yes	No
R^2	0.370	0.585
German Mean	2.484	2.484
N Clusters	273	273
Observations	819	819

Notes: Unit of observation: axis-day. Estimates of Equation 4. Sample period August 1942 to April 1943. Standard errors clustered by date.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$