SOCIAL SCIENCES

Quantifying the Holocaust: Hyperintense kill rates during the Nazi genocide

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Operation Reinhard (1942–1943) was the largest single murder campaign of the Holocaust, during which some 1.7 million Jews from German-occupied Poland were murdered by the Nazis. Most perished in gas chambers at the death camps Belzec, Sobibor, and Treblinka. However, the tempo, kill rates, and spatial dynamics of these events were poorly documented. Using an unusual dataset originating from railway transportation records, this study identifies an extreme phase of hyperintense killing when >1.47 million Jews—more than 25% of the Jews killed in all 6 years of World War II—were murdered by the Nazis in an intense,100-day (~3-month) surge. Operation Reinhard is shown to be an extreme event, based on kill rate, number, and proportion (>99.9%) of the population murdered in camps, highlighting its singularly violent character, even compared to other more recent genocides. The Holocaust kill rate is some 10 times higher than estimates suggested by authorities on comparative genocide.

INTRODUCTION

The Holocaust, the Nazi-German annihilation of European Jewry during World War II (1939–1945), is unarguably one of the most destructive and murderous events in the history of human civilization (*1*–*17*). However, over the last 70 years, genocides and mass killing events have continued to occur and they are not diminishing in frequency (*18*, *19*). Bosnia, Rwanda, Darfur, Burundi, Syria, and Myanmar have all experienced large-scale murder operations in the last 25 years, some of which may have been preventable (*20*, *21*). Developing a deeper understanding of genocides and mass killing events, including their causes, common characteristics, predictability, and mitigation, is thus considered by some as "the most important goal of social science" (*18*). In this respect, lessons learned from the Holocaust continue to play a vital role, and the topic remains as timely as ever.

One of the aims of this paper is to demonstrate the importance of "quantifying" warfare and conflicts by taking the Holocaust as a particular case study. An attempt is made to go beyond conventional questions, such as "How many victims perished?", which has been the main data focus until now. Instead, we quantify how the Nazi war against the Jews evolved in time over an important period during the Holocaust and the rate at which the genocide proceeded. Consider, for example, the recent estimate that 5.4 million to 5.8 million Jews were murdered in the Holocaust in the course of World War II, mostly in the 4 years of mass killings of 1941–1945 [(*9*); breakdown in section S1]. Statements of this nature have limited explanatory power because, in the end, we are left with a single aggregate number that is bewilderingly large and difficult for the human mind to relate to. We gain no insights as to whether the victims were murdered uniformly in the 4 years of mass killings (i.e., 1.5 million per year), as might hypothetically be speculated, or whether there were other patterns or phases in the years of genocidal killing. Even researchers who have studied the Holocaust in detail, and who have some reasonable grasp of the historical timeline, can struggle to provide a simple clear picture of the changing kill rates over extended periods of time. Neither is this information easily found in specialist textbooks, given that they are not particularly specific and offer only limited characterization. However, this is not unexpected since the Holocaust was, after all, a highly complex and chaotic period in history. At various times over the war, the Nazis activated major genocidal death camps and controlled >40,000 Jewish ghettos and concentration camps across Europe [even going back to 1933 when the first camp at Dachau was opened (*17*)], all of which eventually had to be organized for implementing the Nazi leaders' vision for the "Final Solution to the Jewish question." With all this complexity, here we ask, Are there any simple definitive killing patterns that can be distilled from this period that can shed better light on the large-scale dynamics of the Nazi operation? To help answer this question, basic time series tools and spatiotemporal mappings are used to study an unusual dataset collected by Professor Yitzhak Arad (*2*) and to provide a different outlook on the Holocaust that focuses on its dynamically changing character. In the process, we identify kill rates of extreme magnitude that are almost twice as high as the Rwanda genocide and roughly 10 times higher than commonly believed.

This paper is generally concerned with Operation Reinhard, which has been referred to as "the largest single murder campaign within the Holocaust" (*10*). The Operation began in March 1942 and lasted 21 months, concluding in November 1943 (*2*). In this Operation, the three key death camps Belzec, Sobibor, and Treblinka were set up with the intention of eliminating every Jew in German-occupied Poland (*1*–*6*)—the region known as the General Government (GG). The three Nazi "death camps" or "killing centers" were infamous for their industrial mass killings and their ability to rapidly liquidate entire Jewish communities with the aid of gas chamber technology, thereby resulting in a large-scale "Holocaust by Gas." Detailed records of the killings are almost nonexistent because of the Nazis' tight secrecy around Operation Reinhard. Any information that was recorded was deliberately burnt and destroyed by the Nazis during the war for fear of future incrimination. In addition, a large percentage of murders have to be attributed to widespread shooting, since a "Holocaust by Bullets" took place in parallel both in and outside the GG (*6*, *11*).

Because Auschwitz has long been viewed as the central symbol of the Holocaust, the Reinhard death camps have received relatively less attention for many years (*4*). While Auschwitz had a reasonable number of survivors to reconstruct the history, very few survived the camps of Operation Reinhard to convey their experiences. Partly for these reasons, Pohl (*9*) pointed out in 2004 that the three main death

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camps "Belzec, Sobibor and Treblinka became, from the Spring of 1942, the murder site of almost half of Polish Jewry [i.e., ~1.7 million people], but no scholarly camp monograph has yet been published." Only recently have historians been able to reconstruct a reasonably accurate picture of the total numbers of victims who perished at the major death camps (*7*, *8*, *12*, *13*). Although population assessments have been undertaken, the data on human lives are considered so highly sensitive that there have been very few attempts to explore it in any depth beyond coarse-scale summaries. As a result, the literature remains vague on what actually occurred during the chaos of Operation Reinhard, and efforts to address this gap have begun only in recent years (*4*, *10*, *12*, *13*).

The present study relies on Arad's (*2*) carefully compiled dataset of train deportations to the three key death camps. This paper first reconstructs the temporal dynamics of what actually occurred during Operation Reinhard, providing the first aggregated high-frequency time series of killings as the Operation progressed over 1942 and 1943. It uses the time series to expose the unusual speed and kill rate during Operation Reinhard, a characteristic that has been poorly quantified in the past. The rate of killing is found to be an order-of-magnitude larger than the estimates routinely cited by many internationally recognized authorities of comparative genocide (*20*–*28*). Furthermore, the paper graphically shows for the first time that the great bulk of the killings occurred in a rapid 3-month pulse during August to October 1942 (see Fig. 1). To support the analyses, this paper also explores the spatial and spatiotemporal dynamics of Operation Reinhard, as it took place in the GG and over the rail network; it presents simple indices for quantifying mass killings, with a particular focus on "kill rate," and it improves documentation of historical events that took place over the Holocaust with the aid of visual time series, a spatiotemporal video, and basic data analysis.

As indicated, this study also relates to the broader framework that has sprung up in the social sciences over the last two decades, dealing with the patterns and dynamics of warfare, by learning from and by modeling past events (*29*). It helps set the stage for returning to study individual atrocities and rethinking approaches when discussing genocides other than the Holocaust (*18*, *19*). As the Holocaust is often used as a reference frame when studying modern-day genocides, a quantitative view of the Holocaust is essential for understanding how modern genocides differ or are similar to those of the past. The data-driven results obtained here allow us to revisit past comparisons. For example, textbooks and the literature often state that the kill rate of the Rwanda genocide was three to five times more intense than the Holocaust. Our results allow us to quantitatively show that this claim is incorrect and thereby illustrate the importance of accurately quantifying not only the Holocaust but also modern conflicts in general.

Data and railway network

Hitler's plan for a "Final Solution" relied on careful mobilization and scheduling to efficiently shuttle millions of victims, often whole Jewish communities, across the European railway network in train carriages to the death camps, where victims were rapidly murdered

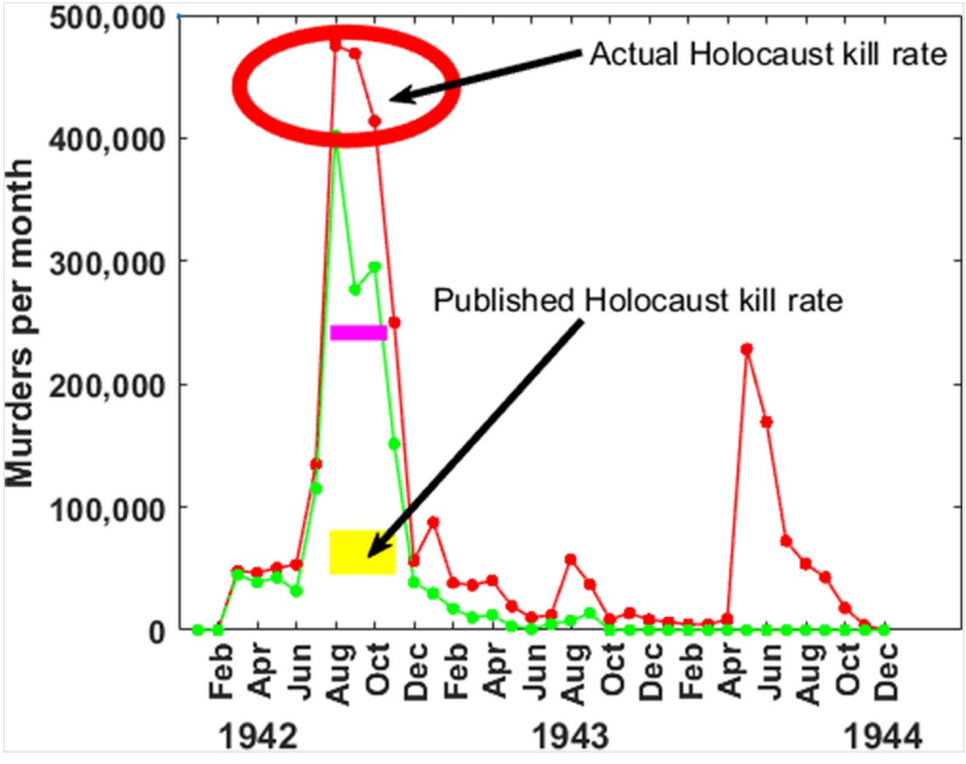


Fig. 1. Holocaust kill rate. Reconstruction of Holocaust monthly kill rate in units of murders per month, totalled for Belzec, Sobibor, and Treblinka death camps and plotted as a green line from January 1942 to December 1944. The superimposed red line is the total number of murders per month after inclusion of Auschwitz victims and Einsatzgruppen shooting victims (see section S1). The actual Holocaust kill rates for the months of August, September, and October 1942 are highlighted by red dots in the ellipse. The large peak in the year 1944 (red line) represents Auschwitz victims. The thick magenta line indicates the Rwanda kill rate (243,300 murdered per month). The thick yellow box indicates the range of Holocaust kill rates based on recent erroneously published estimates that assume it to be one-third to one-fifth as intense as the Rwanda genocide kill rate.

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(*1*–*4*, *10*, *14*). The complex logistics of this effort were solved through the involvement of the *Deutsche Reichsbahn* (German National Railway). The *Reichsbahn* employed almost half a million civil servants and 900,000 workers, who were made available for the job (*1*), and knowingly participated in the killings (*14*, *15*). The *Reichsbahn* shuttled victims in "special trains" that kept to a well-formulated time schedule (section S2). It has been argued that the IBM Corporation also participated in helping to ensure that Hitler's special trains ran on time and provided a punch card system to help achieve this goal (*15*). The *Reichsbahn* railway network was a critical component of the Nazi's blueprint for genocide and destruction. Records of train schedules and movements, fragmentary as they are, have since become an important source of data used to estimate the spatial and temporal patterns of victims who were shuttled to the death camps.

Detailed high-frequency datasets on conflicts and genocides are particularly rare for major historic events before this century, which makes Arad's (*2*) dataset on Operation Reinhard highly unusual. Arad (*2*) meticulously compiled and listed more than 480 train deportations from 393 Polish towns and ghettos to the death camps and provided estimates of the approximate number of victims on each transport. These estimates are based on surviving historical records of the *Deutsche Reichsbahn*, ghetto records, postwar trials, and research studies. The present paper is devoted to the analysis of this dataset that, except for one other independent study (*13*), has not been previously investigated in any depth.

Arad (*2*) compiled data for each of the three death camps, Belzec (~515,000 perished), Sobibor (~126,000 perished), and Treblinka (~897,000 perished). When totalled, the data give reasonable estimates for numbers of the death camp victims. The accuracy and debates surrounding the precise values of the numbers perished are discussed in section S1. However, for the purposes of this analysis, it is not problematical whether the numbers of victims are approximate, since we are interested in either broad trends or reliable estimates of minimum numbers of victims. The dataset lists the dates (day, month, year) and number of deportees for different transports to Belzec, Sobibor, and Treblinka, grouped by spatial location. For the work that follows, it was necessary to organize and sort the data temporally over 1942 and 1943 and use it to construct time series of different levels of spatial and temporal aggregation (see Materials and Methods).

RESULTS

The 3-month "pulse of death"

Operation Reinhard began in March 1942, coinciding with opening of the death camp Belzec and the building of Sobibor and Treblinka (*2*). Other accounts date the Operation back to October 1941. The Operation ended in November 1943 and thus lasted 21 months during which some 1.7 million Jews were murdered in the three death camps (*2*). We would like to know more than these aggregate figures. Were the exterminations carried out at a constant pace? Was there a period of peak activity? How efficient were the death camps in annihilating the Jewish population of the GG? And did they operate simultaneously?

Figure 1 displays the temporal dynamics of Operation Reinhard in time over the period 1942–1943, as largely derived from Arad's (*2*) dataset. In this graph, the monthly total number of victims summed over all three death camps is plotted as it changes in time (visualizations for individual death camps are given in fig. S1 and section S2). The green line graph plots the monthly total aggregate sum of victims from the Belzec, Sobibor, and Treblinka death camps. In the analysis that follows, we will sometimes have interest in going beyond the Operation Reinhard death camps and obtain a bigger picture by including in our calculations murders in the same time period but from outside the GG as well. Thus, the red line combines the Operation Reinhard data, along with data from Auschwitz and the Einsatzgruppen mobile shooting squads, to obtain the total number of victims. It should be emphasized that the numbers plotted represent a realistic minimum lower bound and that the reality was likely greater than indicated in these graphs (see discussion on limitations of estimates in Materials and Methods).

An unexpected outcome of the present time series reconstruction was the uncovering of the huge "burst" of activity in mass killing that manifests as a pulse in Fig. 1. While Operation Reinhard lasted 21 months, these data show that the great bulk of the killing occurred in a huge pulse over the 3 months, namely, August, September, and October, of 1942 (that is, only 14% of the 21 months of Operation Reinhard).

For the two single months of August and September, there were very close to half a million victims each month, who were either gassed to death within hours of arrival at the death camps or shot by the Einsatzgruppen. More broadly, in this 3-month (92 day) period, the data in the graphs indicate that a minimum of 1.32 million victims were murdered by the Nazis, of which 292,000 were murdered by bullets [(*1*); section S1]. Hence, not only is Operation Reinhard the largest murder campaign within the Holocaust: It also happened at a remarkably faster pace than previously recognized.

Unprecedented assembly line dynamics of mass murder

Himmler's order of 19 July 1942 stated that, by the end of December 1942, all the Jews within the GG, with few exceptions, should be liquidated (*1*). These initial guidelines set a time limit for the entire Operation Reinhard, which, although not met in practice, strongly influenced its efficiency and timeline. According to Gerstein's report, on 15 August 1942,

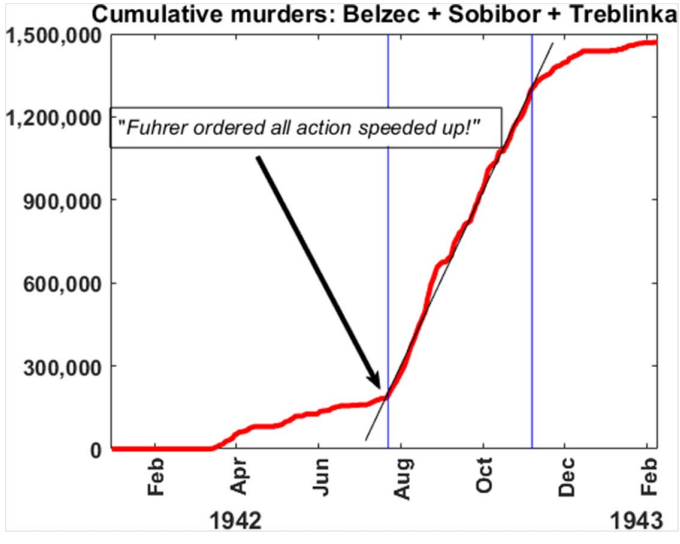


Fig. 2. Cumulative murders. Cumulative number of victims murdered at the three death camps Belzec, Sobibor, and Treblinka beginning from 1 January 1942. Almost all of these victims were murdered soon after arrival at the camps. The blue vertical lines indicate initiation (22 July 1942) and termination (4 November 1942) dates of the 105-day speed-up action in the GG death camps. The constant steep slope over this period indicates that the kill rate persisted at an almost constant rate. Note that this dataset does not include victims from outside the GG as in Fig. 1.

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the "*Fuhrer* ordered all action speeded up!" (*2*). In his book, Gilbert (*5*) devotes the chapter "At a faster pace" to a similar directive, which he dates to 23 July 1942, when the first trainloads of victims from Warsaw ghetto reached Treblinka. Arad's (*2*) data plotted in Fig. 1 indicate that the "speedup" manifested as a sustained activity that was initiated with the emptying of Warsaw ghetto on 22 July 1942 but continued on at a sustained rate for months afterward so that the murdering was almost completely over by December 1942.

Figure 2 shows the speedup as it happened on the ground by plotting the cumulative total number of victims arriving at the three death camps Belzec, Sobibor, and Treblinka on a daily time scale. Qualitatively, the intense speedup from July 22 appears as an abrupt transition in Fig. 2 and, in this respect, is largely responsible for the huge peak noted in Fig. 1. By December 1942, there were relatively few Jews left in the GG and so the rate of the killing likely subsided because of the difficulty of rounding up victims, in reasonable step with Himmler's original order. The graph in Fig. 2 shows that the speedup, exclusively in the death camps, ran for a period of 105 days to 22 July 1942 until 4 November 1942. (Note that this is a different dataset to Fig. 1, which incorporates the impacts of Auschwitz and the Einsatzgruppen and which are given on a monthly basis). The linearity of the cumulative daily deaths in Fig. 2 suggests that the number of trains being used to collect victims was fairly constant throughout the period (see section S2). The intensity of the killing reduced on approximately 4 November after almost all of the Radom District of the GG had been transported to Treblinka and the Belzec death camp was being prepared for closure.

The data shed further insights into the dynamics of death at the camps. Consider first the Treblinka death camp. Figure 3 plots the number of victims arriving by train at Treblinka on a daily basis as reconstructed from (*2*, *3*). In the first wave of train deportations to Treblinka, almost all residents of the entire Warsaw ghetto were transported over the 7-week period beginning 22 July 1942. The first trains were composed of mainly children, the sick, and the elderly who were more easily dealt with. Each day, a train of 50 freight carriages on average made the journey, with each carriage containing more than 100 people, under appallingly crowded and inhumane conditions (*3*). Many died en route. The left-hand section of Fig. 3 (red vertical bars) visualizes the daily Warsaw ghetto deportations, averaging roughly 5000 to 6000 victims per train, in daily trains over the 7-week period July 22 to September 12. The gap seen between August 28 and September 3 corresponds to a stoppage of train deportations due to an inability to handle the masses of corpses that had built up in the overload at Treblinka, which was also exacerbated by breakdowns of the gas chambers (*2*) and a change of the camp Commander.

While this was happening, "some participants [in Warsaw ghetto] maintained quite reasonably that it was impossible to deport half a million people" (*4*). By September 12, at least 254,000 Warsaw ghetto victims had been transported, most of whom were rapidly murdered upon arrival at Treblinka gas chambers, thus giving the system perfected by the Nazis all the characteristics of an automated assembly line. As Hilberg (*1*) noted, a "salient fact about the killing center operations is that, unlike the earlier phases of the destruction process, they were unprecedented. Never before in history had people been killed on an assembly-line basis."

Figure 3 also indicates the spatial organization of the staggered Nazi plan as they transported and liquidated the Jewish populations one district at a time in approximate sequential order: first, Warsaw ghetto (red), followed by the remainder of Warsaw District (dark blue) and then Radom District (green), followed by Lublin (orange) and then Bialystok District (gray). A similarly organized picture is found for the Belzec death camp (fig. S2).

Kill rate of the Holocaust

This analysis allows us to better define and quantify the concept of a genocide's kill rate. The kill rate of the Holocaust, also called the "rate of killing" or "die rate" (*1*), is referred to in this paper by the symbol K_r and measured in units of number of victims murdered per unit time. Genocide scholars have sometimes quantitatively compared rates of recent genocides to the rate at which the Nazi Holocaust

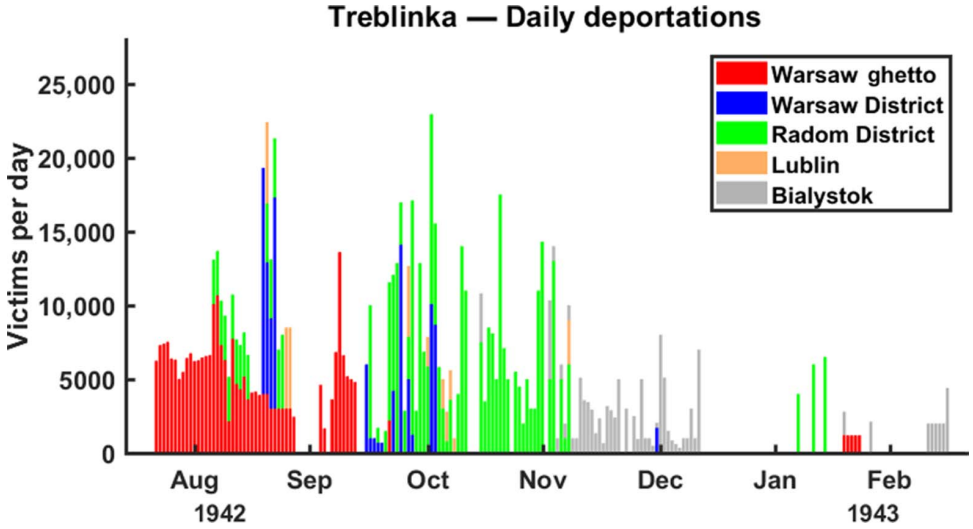


Fig. 3. Deportations to Treblinka. Reconstruction of number of victims transported by train per day to Treblinka as plotted from July 1942 to March 1943, all of whom were murdered with few exceptions. Data are from (*2*) and (*3*). Trains originated from different districts of the GG. Warsaw ghetto (red) = 267,100 victims transported in total (minimum). The remaining Warsaw District (blue) = 103,020, District of Radom (green) = 364,400, Bialystok District (gray) = 117,970, and District of Lublin (orange) = 33,300.

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occurred, treating it as a kind of benchmark for genocide severity (*20*–*28*). The Rwanda genocide of 1994 is a useful case in point, and this massacre is often compared to the Holocaust (*20*–*28*). According to current scholarship, the Rwanda genocide is now viewed by genocide scholars and social scientists as the "most intense" genocide of the 20th century. Perhaps because detailed data within conflicts, similar to those analyzed here, are difficult to obtain, scholars, human rights advocates, policy-makers, and experts on international affairs often repeat the same rough estimates, even if highly erroneous. A sample of typical comparisons with the Holocaust by authorities includes the following:

1) The "yield" of the Rwanda massacre "proved distinctly superior to that of the Jewish and Gypsy genocide…. In 1942, at the height of the shootings and deportations, the Nazi regime and its zealous administration, its chemical industry, its army and police, equipped with sophisticated material and industrial techniques (heavy machine guns, railway infrastructure, index files, carbon monoxide gas trucks, Zyklon B gas chambers…) never attained so murderous a performance level anywhere in Germany or its fifteen occupied countries" (22);

2) "at least eight hundred thousand were killed in just a hundred days," and "the dead of Rwanda accumulated at nearly three times the rate of Jewish dead during the Holocaust" (23);

3) it "was slaughter on a scale not seen since the Nazi extermination programme against the Jews. The killing rate in Rwanda was five times that achieved by the Nazis" (24);

4) the Rwanda genocide was "the fastest, most efficient killing spree of the twentieth century" (21);

5) it "was estimated that the Hutus had killed the Tutsis at a rate of five times a day more than the Nazis had killed the Jews in all the concentration camps" (25); and

6) even in 2017, we read: "Between April and July 1994, hundreds of thousands of Rwandans were murdered in the most rapid genocide ever recorded" (26).

In view of our results so far, we may examine the validity of these comparisons. It is generally acknowledged that some 800,000 of Rwanda's Tutsi population were brutally slaughtered in the space of a 100-day period in 1994 (*21*, *23*, *30*, *31*). That is, approximately 75% of Rwanda's Tutsi population (*30*). Some assessments suggest the casualties are lower and lie between 600,000 and 800,000, and one recent and influential study estimates a lower value of 500,000 (*31*). Here, we will assume the higher value of 800,000, which provides a more conservative estimate.

To make a fair comparison between these two genocides in terms of their kill rates, we focus on whether there was a 100-day period in the Holocaust that had a similar or greater destructive intensity to Rwanda with 800,000 dead over 100 days. A scanning of the data reveals that, for the 100 days beginning 27 July 1942 and ending 4 November 1942, the number of victims of the Holocaust from both within and outside the GG is as follows:

1,072,101 victims murdered at Belzec, Sobibor, and Treblinka;
301,720 Einsatzgruppen deaths by bullet (section S1); and
91,390 Auschwitz victims (*6*), for a total of

1,465,211 TOTAL: K_r(Holocaust) = 1.47 million victims murdered over 100 days
= 445,700 murders per month

The true number of victims per day is quite likely to be greater, as only the key events for which reliable information is available have been included.

In contrast, the kill rate for Rwanda is K_r(Rwanda) = 800,000/100 × 30.42 = 243,300 murders per month, which is indicated in Fig. 1 as a magenta line. Thus, the kill rate in the Operation Reinhard period is approximately 83% higher than the commonly suggested figure for the kill rate in Rwanda, indicating that previous comparisons have been based on incorrect accounting.

As a useful exercise, suppose the claim that the kill rate of the Rwanda genocide [K_r(Rwanda)] was three to five times larger than the kill rate of the Holocaust [K_r(Holocaust)] was correct. For this to be true, the Holocaust kill rate must sit between K_r(Rwanda)/5 and K_r(Rwanda)/3, implying K_r(Holocaust reported in literature) = 48,700 to 81,100 murders per month, as shown in Table 1. This is visualized as the yellow rectangular box in Fig. 1.

However, this value for K_r(Holocaust reported in literature) is only 11 to 18% of the true Holocaust kill rate found through our data analysis based largely on the death camps [K_r(Holocaust) = 445,700 murders per month]. The disparity indicates that the true kill rate of the Holocaust has been routinely underestimated by close to an order-of-magnitude error. In reality, the error should be far worse, given that the data for the estimates in Fig. 1 are approximations and considered minimum estimates.

Spatiotemporal dynamics

Spatial effects can also clarify comparisons of genocides when factored into kill rate calculations. From this perspective, it is notable that Rwanda is less than 20% of the geographic size of the GG and that all Tutsi victims were concentrated together, living alongside the perpetrators of the massacre. In theory, this facilitated the Rwanda

Table 1. The monthly kill rate K_r True for the Holocaust during the Operation Reinhard period (1942–1943) as compared to the Rwanda genocide of 1994. The monthly kill rate K_r Perceived of the Holocaust is calculated from the erroneous claims that K_r(Rwanda) was three to five times larger than the Holocaust kill rate; i.e., K_r(Holocaust Perceived) lies between K_r(Rwanda)/5 and K_r(Rwanda)/3.

	Holocaust (1942)	Rwanda (1994)
K_r True (monthly kill rate)	K_r(Holocaust) = 445,700 murders per month	K_r(Rwanda) = 243,300 murders per month
K_r Perceived (monthly kill rate) reported in literature and by media	K_r(Holocaust reported in literature) = [K_r(Rwanda)/5 to K_r(Rwanda)/3] = [243,300/5 to 243,300/3] = [48,700 to 81,100] murders per month = [11 to 18%] K_r(Holocaust)	K_r(Rwanda) = 243,300 murders per month

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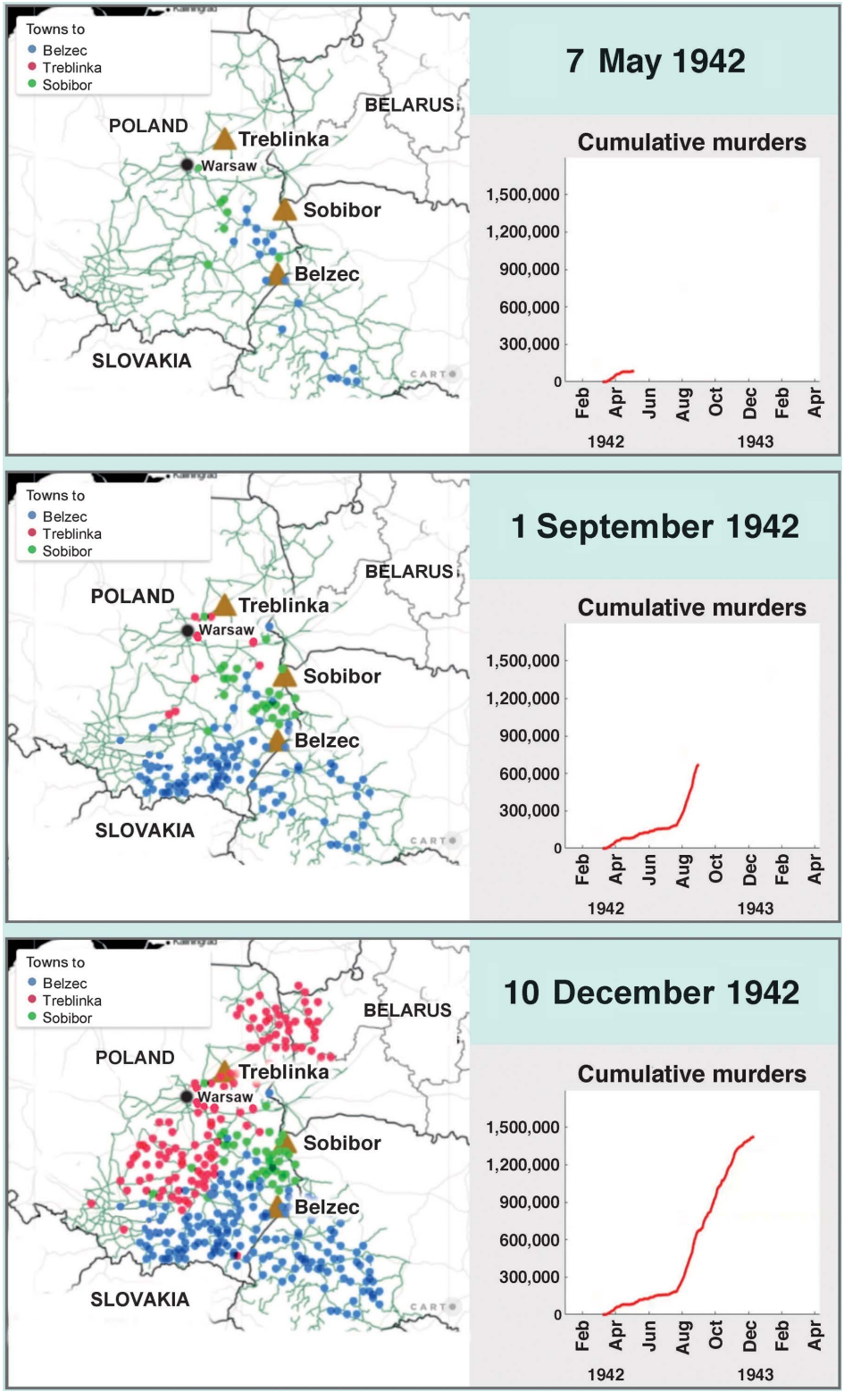


Fig. 4. Spatiotemporal dynamics of death camp deportations. Three screenshots, from film S1 in section S4, provide reconstructed maps of the train deportations in the GG on the dates 7 May 1942 (top), 1 September 1942 (middle), and 10 December 1942 (bottom). The three death camps are indicated by labeled brown triangles. The source points of the towns or Jewish communities are plotted in different colors, depending on whether they perished at Treblinka (red dots), Belzec (blue dots), or Sobibor (green dots). The solid green lines represent the railway tracks of Poland. By 10 December 1942, almost all Jewish communities in the GG had been transported to the death camps. The right-hand panels plot the increase in the cumulative number of deaths as the genocide proceeded in time (i.e., from the top map to the bottom map). Maps were constructed using CartoDB software.

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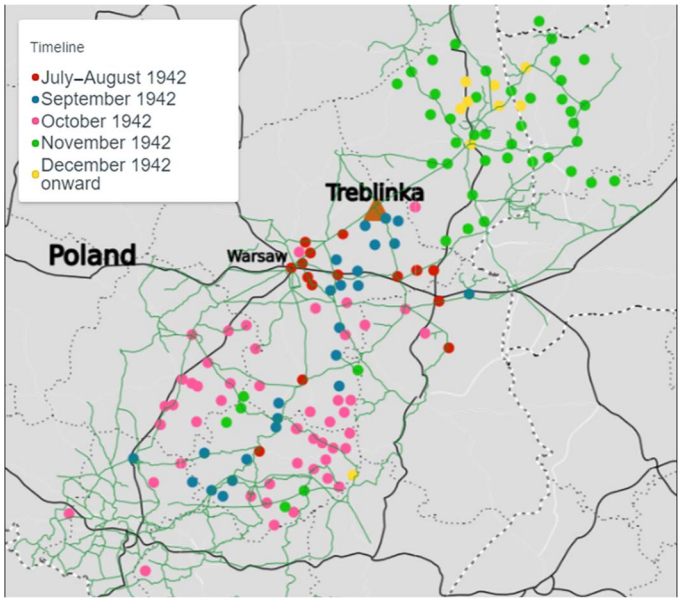


Fig. 5. Treblinka. The sites of the many Jewish communities listed in the Arad (*2*) dataset that were deported to Treblinka by train. The communities deported in July to August 1942 are marked as red dots, and those in the months of September, October, November, and December are marked as blue, purple, green, and yellow dots, respectively. The solid green lines represent the railway tracks of Poland, which create a network that forms the background structure for the deportations. Thus, September train deportations were focused on collections along the major rail line that sits approximately on the 45° diagonal (blue dots). Map was constructed using CartoDB software.

massacre considerably. In contrast, the assembly line killing of the Holocaust relied heavily on a geographically dispersed train network that could require days at a time to transport victims from locations across Poland and concentrate them at the death camps. Despite its broad spatial extent, Operation Reinhard ran at a substantially higher kill rate for sustained time lengths, as compared to the Rwanda genocide.

The actual spatiotemporal dynamics can be reconstructed direct from Arad's (*2*) data and has been visualized in film S1. The film S1 illustrates the sequential train deportations in maps of towns across the GG continuously over the period 1942–1943. Three screenshots from the film are reproduced in Fig. 4, representing maps for the dates 7 May 1942 (top), 1 September 1942 (middle), and 10 December (bottom). In each map, the locations of the three death camps are indicated by the labeled brown triangles. The source points or collection points of the Jewish communities are plotted in different colors, depending on whether they were transported to and perished at Treblinka (red), Belzec (blue), and Sobibor (green).

The film and maps show the intense and calculated rounding up of the Jewish populations, beginning with those that perished at Belzec on March 15, followed by Sobibor on May 3, and lastly followed by Treblinka (close to Warsaw) on July 22. The last main communities in Bialystok were rounded up in November and December 1942 (top right corner of mapping, on the periphery of the GG). In October and November, all three camps were operational simultaneously, although at different rates and each concentrating on a different area of the GG. Sometimes, there were several deportations from a single town or station at different times of the year, which are visualized here as the same single point. We note that, within the GG, the communities transported to Belzec were spread over a larger terrain than those of the other camps, while Treblinka received the most victims overall. The structure of the railway network (green lines) itself can be seen in these data, where communities are transported sequentially along long stretches of the rail line.

The right-hand panels in the film and in the maps of Fig. 4 plot the increase in the cumulative number of deaths as the genocide proceeded in time. Last, by late November 1942, the graph plateaus, indicating approximately ~1.5 million cumulative murders. Arad (*2*) indicates that there were close to another 200,000 murders in Belzec and Sobibor that went unrecorded in his dataset, which would raise the total number of deaths to 1.7 million (section S1).

In the last map of Figure 4 for 10 December 1942, one notes that almost all Jews in the GG had been transported to the death camps. Furthermore, all the Jewish communities that were transported divide into three compact clusters colored red, green, and blue. The presence of these clusters corroborates what is known in the Holocaust literature, namely, that the train trips were organized according to proximity to the death camps and the zones of the GG (*2*) and that the trains flooded the GG area for a period of a few months only. What happened to the single locality Warsaw ghetto at one point in space was applied thoroughly across the entire region, leaving no Jewish community in the GG unscathed.

Figure 5 zooms in on the train deportations to Treblinka over 1942. Deportations in the last week of July and the month of August 1942 are marked in red, and those in the months of September, October, November, and December are marked in blue, purple, green, and yellow, respectively. The solid green lines represent the railway tracks of Poland, which create a network that forms the background structure for the deportations. Thus, September train deportations were focused on collections along the major rail line that sits approximately on the 45° diagonal (blue dots). The October deportations concentrate on two parallel rail lines: one north and the other south of the September collections. The time sequence aligns reasonably well with the spatial sequence of districts that we have already noted, namely, Warsaw (red) in July and August, followed by Radom District, Lublin, and lastly, in November and December, Bialystok District (green and yellow). This temporal sequence of events also perfectly corroborates events known to have occurred and that are documented in the literature (*2*), suggesting that our time series analysis of kill rates is reasonably accurate.

DISCUSSION

Operation Reinhard

The Nazis' extremely efficient extermination machine presumably could have continued to run smoothly for many more months at the kill rates identified here had there been a continuous supply of victims in the GG. Instead, the enormous pulse of death in Fig. 1 during 1942 consumed the large majority of possible Jewish victims. The subsequent rapid plunge in the death rate in November and December 1942 simply reflects that there were very few Jewish victims left alive to murder by this stage in the GG. The Nazi agenda was then revised to transport and murder the remaining Jewish populations of Europe to the Auschwitz-Birkenau extermination facility. Auschwitz was operating on a continual basis from 1941 but had exceptionally high kill rates in 1944, as evidenced by the very large peak around that time in Fig. 1 (the main component of the peak is due to the Hungarian deportations to Auschwitz).

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That the mass killings of Operation Reinhard mostly occurred in a 3-month period likely created substantial confusion among the victims, and its speed would have made the possibility of organized resistance difficult to coordinate in time. That is, the massacre was effectively over before there was time for an organized response. Despite this, some resistance operations occurred (*1*, *2*). The analysis presented here provides clear evidence of markedly high rates of genocide in a markedly small period of time, so much so that nearly 25% of all Jewish victims of the Holocaust were murdered during 3 months of Operation Reinhard in 1942.

In addition to being supported by data, these staggering numbers and rates are corroborated by survivors' testimonies. At the Belzec death camp, some 600,000 Jews were exterminated (*2*). Rudolf Reder, one of only two survivors of the Belzec death camp, gave the following testimony in 1944 (*32*):

> This was a long period of intensified murder of Jewish people. I was told by prisoners ….. that the number of "transports" sent to Belzec during September, October and November 1942 was much greater than the "transports" sent previously. During these three months the greatest number of Jewish people were murdered….
> During those three months I saw every day a "transport" of 50 wagons with 100 prisoners in each wagon, that is 5,000 victims sent to Belzec. A second identical "transport" arrived every evening. These prisoners were held in the suffocating wagons without food or water until 6 o'clock the following morning. A minimum of 10,000 victims were murdered every 24 hours. There were days that three "transports" arrived. There were days that more than 50 wagons were hauled in each "transport." The "transports" came seven days a week.

A similar nightmare was taking place at Treblinka simultaneously. Aron Gelberd, who eventually escaped from Treblinka, wrote that, in October 1942, for the 19 days he was imprisoned, he witnessed three to four train transports arriving each day with additional transports sometimes arriving at night (*2*).

Of the roughly 800,000 victims who entered Treblinka, there were only approximately 50 survivors (*6*), and a similar number survived Sobibor (*2*). These rates are sufficiently small that the decimation proportions (K_p) of the death camps are nearly complete, with K_p = 99.99% of all victims who were under direct Nazi control being murdered (see Materials and Methods for discussion of indices). A similar decimation rate applies for the whole GG region. By late 1943, approximately 60,000 to 100,000 resistance workers from the Jewish underground were still alive (*9*), indicating a decimation proportion in the GG region of K_p = 94 to 97% [this figure does not include the approximately 100,000 Jews still kept alive as a source of labor for the Nazis in labor camps (*9*)]. This percentage aligns with that given by Pohl (*9*), who reported a proportion of K_p = 98% of the Lublin District in the GG being murdered. In short, the genocide was almost total in the GG area. According to Gerlach (*12*), the mass shootings in the Ukraine were at least as shocking, and "Jewish Actions" were embarked on in August to October 1942 for which the Commander of the Security Police writes "it has been clarified that generally one hundred percent solutions have to be carried out" (*12*).

Thus, the relatively enormous power of the Nazi regime led to the almost complete decimation of the Jewish people in the GG. While this was not always the case for other locations or periods over the Holocaust, neither was it a singular occurrence. For example, Arendt (*33*) noted that, in Holland, "103,000 Jews were deported to the death camps …. Only five hundred and nineteen Jews returned from the death camps," corresponding to a decimation rate of K_p = 99.5%. More recent assessments suggest that this figure is likely to be closer to K_p = 99%.

Relation to previous work

In the last two decades, there have there been other attempts to make a larger reckoning of the pace of the killing over the year 1942, but they are usually presented in broad summary terms that are less precise. Browning's (*34*) work, which might be considered a precursor to the discussion here, wrote that, in the 13 months between January 1942 and mid-February 1943, nearly 1.75 million Jews must have died in west and central Poland, and "most of the massive killing had in fact been carried out in the brief five months following Himmler's meeting with Hitler on July 16 [1942]." It is not clear how Browning calculated a 5-month interval, although it is logical according to the historical sequence of events (e.g., knowledge of Belzec and Treblinka's respective activity timelines), as opposed to being based on direct data analysis. It is not clear how many victims perished in the 5-month interval that Browning mentioned. Neither is there a monthly breakdown of the kill rate, as in Fig. 1, nor any clear notion of a 3-month pulse. Most previous attempts to understand the number of victims who perished in this period follow Browning's approach of "working backwards" by examining the Jewish population at the beginning and end of 1942 and then subtracting [e.g., (*2*, *8*, *10*)]. In contrast, the approach here focuses on exploiting detailed data on transportation activities of Operation Reinhard to document the pace of killing as it progressed. Thus, the time series in Figs. 1 and 2 provide a description of the tempo of Operation Reinhard.

Apart from the Browning quote and several other similar statements, there has been little else in the voluminous Holocaust literature that attempts to give a detailed summary picture of the short intense mass killings during the Operation Reinhard period until recently. Gerlach (*12*) gives a summary conclusion that "About 3 million Jews perished from May to December 1942, 2 million in the four horrible months from July to October 1942 alone." However, Gerlach (*12*), who is approximately correct with these figures, does not give the full calculation that led to the conclusion nor any reason for isolating a 4-month period. His statement presumably relies on the German doctoral thesis of Berger (*13*) who gives figures that are accurate for the three different death camps, but not beyond that. Both studies complement the present paper, as discussed in more depth in section S3.

Concluding remarks

Especially when comparing modern genocides, historians, social scientists, policy-makers, and journalists have consistently relied on inaccurate assessments that greatly underestimated the Holocaust kill rate during Operation Reinhard. These underestimates have been repeated for nearly two decades without substantial criticism, a pattern that has effectively rewritten the history of the Holocaust in a way that diminishes its historical standing and the scale of human life it encompasses. These underestimates have arisen and persisted because of a lack of awareness of the details concerning the Reinhard death camps and the effectiveness of the Nazi efforts to obscure those details during the war. Our analyses shed new light on this period of the Holocaust and provide a clearer and detailed picture of the dynamics and rates of the major events as they unfolded during Operation Reinhard.

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The assembly line efficiency of murder by the Nazis and the capability to reach and maintain these high kill rates were an outcome of having the key death camps operating simultaneously for a period, supported by the railway system to rapidly transport Jewish victims to the camps. The deportation trains were only a small fraction of the rail traffic of the time and thus likely a relatively small exercise for the *Deutsche Reichsbahn* to orchestrate (*14*). The results of this modest effort by the *Reichsbahn* illustrate the substantial power at the disposal of the Nazi leaders to target and destroy their enemies. For these reasons, Operation Reinhard was extreme in terms of three elementary indices of the severity of a genocide—kill rate, number, and proportion of population killed (>99.99% in death camps and >94% in GG)—which highlights the singularly violent character of this genocidal event.

MATERIALS AND METHODS

Time series

Arad (*2*) lists the dates (day, month, year) and number of deportees for different transports to Belzec, Sobibor, and Treblinka, grouped by spatial location. Figure 4 provides spatial plots of the many towns and communities recorded in the dataset. The data were organized and sorted temporally over 1942 and 1943 to construct the following:

1) a time series for each death camp on a daily time scale (see Fig. 3 and figs. S1 and S2);

2) an aggregate time series of the data from the three death camps on a daily time scale (basis for Fig. 2);

3) an aggregate monthly time series with added complementary data including that for Auschwitz (~1,081,000 perished) from (16), which was not formally part of Operation Reinhard, and that for mobile shooting squads, or Einsatzgruppen, from (1). The complementary datasets necessitated using a monthly time scale (see Fig. 1); and

4) spatial maps of the deportations (Figs. 4 and 5) and a spatio-temporal film S1 (section S4).

The final time series and datasets contain dates, approximate numbers of victims, and their source locations and destinations, as described further in section S1.

Elementary indices of mass killing events

Some further remarks and warnings are necessary concerning simple procedures for comparing genocides, as routinely applied in the literature. Usually, this entails making use of one or more standard quantitative indices, often none of which are more correct or more valid than any other. An obvious index is

$$K_{\#} = \text{Total number of victims killed}$$

Clearly, the Holocaust has an extreme number of victims [$K_{\#}$(Holocaust) = 5.4 million to 5.8 million dead], even compared to most other genocides [e.g., $K_{\#}$(Rwanda) ≈ 800,000 dead]. So huge is the number that it falls outside the range of victims in Krain's (*18*) listing of 35 genocides and politicides between 1948 and 1982 and in Harff's (*35*) listing of 41 genocides and politicides between 1955 and 2005.

Another common index is

$$K_p = \text{proportion of the population who were murdered or decimated}$$

One of the most horrific attributes of Operation Reinhard is that, of the 1.7 million victims in the GG area, there were only very few survivors (*2*, *6*). The genocide was characterized by almost complete extermination in this geographically large area with some tens of thousands of survivors only (*6*), so that K_p = 94 to 97% in the GG and K_p > 99.9% in the death camps.

A third mass killing index is

$$K_r = \text{the kill rate of the population} = [\text{number killed in } \tau \text{ days}]/\tau$$

This is a useful quantitative index as long as the time frame or window is chosen in an appropriate manner. For the genocides examined here, τ = 1 day would be far too small and possibly lead to large fluctuations in kill rates that might not be informative. Conversely, too large a value for τ (e.g., τ = 10 years) would not be representative. For the Operation Reinhard period, with a window of τ = 100 days

$$\begin{aligned} K_r(\text{Holocaust}) &= [\#\text{ killed in 100 days}]/100\text{ days} \\ &= 14{,}700\text{ murders per day} \\ &= 445{,}700\text{ murders per month} \end{aligned}$$

Here, the 100-day window is chosen to maximize K_r.

For Rwanda, for the same time window, τ = 100 days and

$$\begin{aligned} K_r(\text{Rwanda}) &= 800{,}000/100 = 8{,}000\text{ murders per day} \\ &= 243{,}300\text{ murders per month} \end{aligned}$$

Clearly, two different indices may fail to rank the same dataset in the same way, and contradictory conclusions can easily arise for the same dataset. This opens the door for researchers to choose the index that suits their particular agenda best, and therefore, reasonable caution is needed when interpreting any analysis.

For the Holocaust, all of the above three indices K_r, K_p, and $K_{\#}$ are unusually large, which would indicate that it is an extreme event, even in comparison to other recent genocides. Yet, there have been debates in the literature over whether the Holocaust is an extreme event (*36*).

Limitations of estimates

The calculations of deaths in the Operation Reinhard period, as presented here, did not include data from many other camps operating at the time, such as Majdanek, Chelmno, and Stutthoff, and indeed without consideration of any of the other >40,000 Jewish ghettos and concentration camps where death was a daily event across Europe (*17*). There should be well over half a million Jews who lost their lives when hiding, which were also not considered. Moreover, murders of Gypsies (Roma) or other minority groups have not been included [e.g., (*12*)]. The 3 million non-Jewish Poles who were murdered over the war were also not included in the calculation.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/1/eaau7292/DC1

Section S1. Background materials and data

Section S2. Visualization of data from death camps, and materials on train deportations

Section S3. Related studies

Section S4.

Film S1. Deportations of Jewish communities in the General Government 1942.

Fig. S1. Number of victims deported to the death camps per month, with almost all being murdered, plotted as a function of time (months) from 1 January 1942.

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Fig. S2. Reconstruction of number of people transported by train daily to Belzec death camp, all of whom were murdered with almost no exception.
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