The COVID-19 online shadow economy

Alberto Bracci\textsuperscript{1}, Matthieu Nadini\textsuperscript{1}, Maxwell Aliapoulios\textsuperscript{2}, Damon McCoy\textsuperscript{2}, Ian Gray\textsuperscript{3}, Alexander Teytelboym\textsuperscript{4,5}, Angela Gallo\textsuperscript{6}, and Andrea Baronchelli\textsuperscript{1,7,8,*}

\textsuperscript{1}City, University of London, Department of Mathematics, London EC1V 0HB, UK
\textsuperscript{2}Center for Cybersecurity (CCS), New York Univ. Tandon School of Engineering, Brooklyn, NY 11201, USA
\textsuperscript{3}Global Intelligence Team, Flashpoint. New York, NY 10003, USA
\textsuperscript{4}Institute for New Economic Thinking, Oxford Martin School, University of Oxford, Oxford OX2 6ED, UK
\textsuperscript{5}Department of Economics, University of Oxford, Oxford OX1 3UQ, UK
\textsuperscript{6}Department of Finance, Cass Business School, London EC1Y 8TZ, UK
\textsuperscript{7}UCL Centre for Blockchain Technologies, University College London, UK
\textsuperscript{8}The Alan Turing Institute, British Library, 96 Euston Road, London NW12DB, UK
\textsuperscript{*}Corresponding author: Andrea.Baronchelli.1@city.ac.uk

The COVID-19 pandemic has reshaped the demand for goods and services worldwide. The combination of a public health emergency, economic distress, and disinformation-driven panic has pushed customers and vendors towards the shadow economy. In particular Dark Web Marketplaces (DWMs), commercial websites easily accessible via free software, have gained significant popularity. Here, we analyse 472,372 listings extracted from 23 DWMs between January 1, 2020 and July 7, 2020. We identify 518 listings directly related to COVID-19 products and monitor the temporal evolution of product categories including Personal Protective Equipment (PPE), medicines (e.g., hydroxychloroquine), and medical frauds (e.g., vaccines). Finally, we compare trends in their temporal evolution with variations in public attention, as measured by Twitter posts and Wikipedia page visits. We reveal how the online shadow economy has evolved during the COVID-19 pandemic and highlight the importance of a continuous monitoring of DWMs, especially when real vaccines or cures become available and are potentially in short supply. We anticipate our analysis will be of interest both to researchers and public agencies focused on the protection of public health.

Introduction

COVID-19 gained global attention when China suddenly quarantined the city of Wuhan on January 23, 2020\textsuperscript{1} Declared a pandemic by the World Health Organization on March 11, 2020, at the moment of writing the virus has infected more than 18,000,000 people and caused over 650,000 deaths worldwide\textsuperscript{2}. Measures such as social distancing, quarantine, travel restrictions, testing, and tracking have proven vital to containing the COVID-19 pandemic\textsuperscript{3}. 
Restrictions have shaken the global economy and reshaped the demand for goods and services worldwide, with an estimated 2.5 – 3% GDP loss each month since the crisis started. Demand for many products has fallen; for example, Brent oil decreased from 68.90 USD a barrel on January 1, 2020 to 43.52 USD as of August 2, 2020. Meanwhile demand for other products, like toilet paper, dramatically increased. As a result of increased demand, some products are in short supply. Individual protective masks were sold in the United States at 7 USD on February 2, 2020 and the price of alcohol disinfectant doubled on July 1, 2020 in Japan.

As a result, anti-gouging regulations were introduced to control prices, which significantly affected the public attention on products related to COVID-19. As this trend has continued, further exacerbated by online disinformation, numerous customers have sought to fulfill their needs through illicit online channels.

DWMs offer an easy access to the shadow economy through user-friendly websites accessible via specialized browsers, like The Onion Router (Tor). These online markets offer a variety of goods including drugs, firearms, credit cards and fake IDs. The most popular currency on DWMs is Bitcoin, but other cryptocurrencies are accepted for payment as well. The first modern DWM was the Silk Road, launched in 2011 and shut down by the FBI in 2013. Since then, dozens more DWMs have sprung up and many have shut down due to police action, hacks or scams. Today, DWMs form an ecosystem that has proven extremely resilient to law-enforcement. Whenever a marketplace is shut down, users swiftly migrate to alternative active marketplaces and the economic activity recovers within a matter of days.

In this study, we analyse 472,372 listings extracted from 23 DWMs between January 1, 2020 and July 7, 2020. We identify 518 COVID-19 specific listings that range from protective masks to hydroxychloroquine medicine. These listings were observed 7,159 times during this period, allowing us to investigate their temporal evolution. We then compare this COVID-19 related shadow economy with public attention measured through Twitter posts (tweets) and Wikipedia page visits. Finally, we inspect listings that mentioned delays in shipping or sales because of COVID-19. Our results significantly extend previous analyses that surveyed 222 COVID-19 specific listings extracted from 20 DWMs on a single day (April 3, 2020) and - to the best of our knowledge - offer the most comprehensive overview of the DWM activity generated by the ongoing pandemic.

Background: Dark Web Marketplaces

The online shadow economy is as old as the Internet. The first reported illegal online deal involved drugs and took place in 1972. The World Wide Web facilitated the emergence of online illicit markets but the first markets could not guarantee anonymity and facilitated the traceability of users by law enforcement.

Modern DWMs originated and still operate online, but outside the World Wide Web in an encrypted part of the Internet whose contents are often not indexed by standard web search-engines. The Silk Road marketplace was the first modern DWM, launched in 2011. It combined the use of the Tor browser to communicate and Bitcoin to exchange money, allowing the anonymous online trading of drugs and other illegal products. After the FBI shut down Silk Road in 2013, new marketplaces quickly appeared, offering drugs, firearms, credit cards, and fake IDs. These markets also adapted to further increase the level of privacy and security offered to users such as the Invisible Internet Project (I2P) and escrow checkout services.
DWM trade today is worth at least several hundreds of millions of USD per year, and involves hundreds of thousands of buyers and vendors. As a result, law enforcement agencies have put considerable effort into combating them. Furthermore, DWMs have been targets of cybercriminal actors through use of distributed denial-of-service (DDoS) attacks, hacking attempts, and some even shut down autonomously due to administrators stealing funds from customers directly. However, DWMs have organised into a robust ecosystem which has proven exceptionally resilient to closures and whenever a marketplace is closed, the users trading higher volumes of Bitcoins migrate to active marketplaces or establish new ones.

The resiliency and functioning operations of modern DWMs are possible partially because of numerous websites and forums where users can share their experience. One example is Dread, a Reddit-like forum created in 2018 after the closure of the dedicated pages on Reddit. Other ad-hoc platforms exist to monitor whether known marketplaces are active or currently unavailable. Other mechanisms to enhance the resilience of these marketplaces and build trust towards the marketplace and its vendors include feedbacks and ratings. In most marketplaces, buyers have to leave feedback and a rating after a purchase, similarly to what happens on legal online marketplaces. Additionally, marketplace administrators often act as vendor moderators by banning vendors or specific categories of products. Examples include DarkBay, where banned categories include human trafficking, contract killing and weapons, or Monopoly marketplace, where COVID-19 fake vaccine listings were recently banned by moderators.

It is hard to estimate how many live dark web marketplaces currently exist. Recent reports include independent researcher Gwern, which identified 19 live platforms on April 22, 2020, the website dark-net-stats, which registered 10 live “established” marketplaces on May 27, 2020, and the already cited report which crawled 20 different websites. Currently established marketplaces include Empire, Hydra and White House marketplaces.

Data and methods

Dark web marketplaces

The listings used for our study were obtained by web crawling DWMs. Web crawling consists of extracting data from websites and is performed by specialized software. Web crawling DWMs is a challenging task because crawlers must bypass several protective layers. Most of the DWMs require authentication and some even require a direct invitation from a current member. Strong CAPTCHAs are implemented to avoid otherwise easy and automated access to the online marketplace. Several research groups tried to overcome these challenges. For instance, the HTTrack software was used in a combination of PHP, the cURL library, and MySQL was proposed in the python library scrapy was adopted in and an automated methodology using the AppleScript language was utilized in. There are currently very few open source tools available often leaving companies and federal agencies to rely on commercial software. Downloading content from DWMs remains a challenging task, which becomes even harder when the objective of the research study requires monitoring multiple marketplaces for a prolonged period of time.

Our dataset contains listings crawled by 23 DWMs between January 1, 2020 and July 7, 2020 by Flashpoint Intelligence. The pipeline of crawling consists of entering DWMs and downloading key
attributes for each active listing, as highlighted in Figure 1. Each DWM was crawled for at least 90 different days. We categorized the COVID-19 specific listings into five categories: PPE, medicines, medical frauds, tests, and ventilators. Only a fraction of the selected listings were actual COVID-19 specific listings, since mitigation measures to prevent COVID-19 spreading have also impacted illegal trades of other listings. For instance, a vendor might sell cocaine and mention shipping delays due to COVID-19. We included such cases in the category COVID-19 mentions. Categories and relative examples of the listings are presented in Table 1. For details about data pre-processing, see Appendix A where we explain how we select listings related to COVID-19 and how we classify them in categories. We remark that our pre-processing pipeline is biased towards the English language, and this constitutes a limitation of our work.

Table 1: Categories used to classify the selected COVID-19 dataset. The first five categories constitute COVID-19 specific listings, while the last one, called COVID-19 mentions, includes listings mentioning one of the keywords in Table 5 without selling actual COVID-19 specific listings.

| Category           | Examples                                                   |
|--------------------|------------------------------------------------------------|
| PPE                | gloves, gowns, masks, n95                                |
| Medicines          | azithromycin, chloroquine, azithromycin, favipiravir, remdesivir |
| Medical Frauds     | antidotes, vaccines, allegedly curative recreational drug mixes |
| Tests              | diagnosis, test                                           |
| Ventilators        | medical ventilators                                       |
| COVID-19 mentions  | computer, drugs, scam (excluding listings in the medical frauds category) |

Overall, our dataset includes a total of 472,372 unique listings, which can be observed a total of 4,088,840 times between January 1, 2020 and July 7, 2020. In Table 2 we report the breakdown of the
number of unique listings and their total observations in each of the 23 DWMs. In 11 marketplaces (Black Guns, Cannabay, Darkseid, ElHerbolario, Genesis, Hydra, MEGA Darknet, Rocketr, Selly, Skimmer Device, and Venus Anonymous) we did not find any mention of COVID-19. This makes sense as these markets are less generalized and primarily focused on specific goods with specific listing text structure. A brief description of each marketplace together with its specialization can be found in Table 7. In the remaining 12 marketplaces, there are a total of 4,010 unique listings related to COVID-19, which constitutes less than 1% of the entire dataset. These listings were mostly composed of drugs that reported discounts or delays in shipping due to COVID-19. Listings concerning more specific COVID-19 goods such as *masks*, *ventilators*, and *tests* were available on seven marketplaces (Connect, DarkBay/DBay, DarkMarket, Empire, CanadaHQ, White House, and Yellow Brick). There were 518 total COVID-19 specific listings in this markets which were observed 7,159 times during the analysed time period.

Table 2: This table reports the number of days each marketplace was crawled, the number of unique listings, all and COVID-19 specific, and the number of listing observations, all and COVID-19 specific. CanadianHQ indicates The Canadian HeadQuarters marketplace.

| Name marketplace       | Days crawled | Listings All | Listings COVID-19 specific | Observations All | Observations COVID-19 specific |
|------------------------|--------------|--------------|----------------------------|-----------------|--------------------------------|
| Black Market Guns      | 163          | 18           | 0                          | 2,934           | 0                              |
| CanadaHQ               | 94           | 21,853       | 3                          | 145,202         | 53                             |
| Cannabay               | 119          | 1,074        | 0                          | 1,303           | 0                              |
| Cannazon               | 100          | 2,760        | 0                          | 4,606           | 0                              |
| Connect                | 179          | 476          | 2                          | 13,579          | 23                             |
| DarkBay/DBay           | 127          | 105,921      | 421                        | 554,535         | 6570                           |
| DarkMarket             | 92           | 32,272       | 19                         | 37,742          | 20                             |
| Darkseid               | 189          | 8            | 0                          | 1,512           | 0                              |
| ElHerbolario           | 186          | 13           | 0                          | 1,430           | 0                              |
| Empire                 | 107          | 26,010       | 33                         | 93,163          | 46                             |
| Genesis                | 188          | 216,792      | 0                          | 2,174,217       | 0                              |
| Hydra                  | 189          | 297          | 0                          | 37,665          | 0                              |
| MEGA Darknet           | 135          | 754          | 0                          | 1,596           | 0                              |
| Plati.Market           | 189          | 11,678       | 0                          | 17,214          | 0                              |
| Rocketr                | 189          | 460          | 0                          | 7,843           | 0                              |
| Selly                  | 91           | 462          | 0                          | 1,523           | 0                              |
| Shoppy.gg              | 189          | 8,412        | 0                          | 486,819         | 0                              |
| Skimmer Device         | 189          | 12           | 0                          | 2,268           | 0                              |
| Tor Market             | 130          | 634          | 0                          | 25,328          | 0                              |
| Venus Anonymous        | 177          | 84           | 0                          | 14,644          | 0                              |
| White House            | 96           | 21,377       | 5                          | 320,360         | 118                            |
| Willhaben              | 189          | 14,626       | 0                          | 45,774          | 0                              |
| Yellow Brick           | 117          | 6,379        | 33                         | 97,583          | 329                            |
| Total                  | > 90         | 472,372      | 518                        | 4,088,840       | 7,159                          |

**Twitter**

We sampled tweets related to COVID-19 using a freely available dataset introduced in Chen et al. We downloaded the tweets ID from the public github repository. We then used the provided script to recover the original tweets through the python library *twarc*. We studied the temporal evolution of the number of tweets mentioning selected keywords, like chloroquine. In line with our dataset of DWM listings, most of the tweets considered were written in English and the time period considered ranges from January 21,
Wikipedia

We used the publicly available Wikipedia API[23] to collect data about the number of visits at specific pages related with COVID-19, like chloroquine. The Wikipedia search engine was case sensitive and we considered strings with the first letter uppercase, while the others lowercase. We looked for the number Wikipedia page visits in the English language from January 1, 2020 to July 7, 2020.

Results

We assessed the impact of COVID-19 on online illicit trade along three main criteria. First, we focused on the 7 marketplaces containing at least one COVID-19 specific listing, analysing their offers in terms of the categories PPE, medicines, medical frauds, tests, and ventilators, as introduced in Table 1. Second, we considered the 12 marketplaces that included at least one listing in one of the categories in Table 1, thus adding listings to the COVID-19 mentions category in our analysis. We investigated the relationship between major COVID-19 events, public attention, and the time evolution of the number of active listings. Third, we quantified the indirect impact that COVID-19 had on all 23 marketplaces under consideration by tracking the percentage of listings mentioning the themes of lockdown, delays and sales. We linked their frequency to major COVID-19 events.

Categories of listings

Here, we focus on the 518 COVID-19 specific listings present in our dataset, observed 7,159 times between January 2020 and July 2020. PPE is the most represented category, with 343 unique listings (66.2% of COVID-19 specific listings) observed 5,536 times (77.3% of observations of COVID-19 specific listings). The second most represented category is medicines, with 132 (25.5%) unique listings observed 1,276 (17.8% of all) times. Some medicines listings, which are often sold together, included 59 chloroquine listings, 56 hydroxychloroquine listings, and 30 azythromicin listings. Other medicines included 5 favipiravir listings, 3 remdesivir listings, and 1 lopinavir listing. A breakdown of the medicines category together with a brief description of the specific drugs can be found in Table 8, and multiple medicines are sometimes sold in the same listing. We classified 31 (6.0%) unique listings as medical frauds, which are listings that promised immunity from COVID-19 (no such product exists, at the moment of writing), or supposed devices able to detect COVID-19 in the air. These listings also included illicit drug mixes sold as cures. We also registered 10 test (1.9% of COVID-19 specific listings) and 2 ICU ventilator (0.4%) listings. More details on these listings together with some examples are reported in Appendix B. The total number of vendors selling COVID-19 specific listings was 131. Additionally, sellers posted multiple listings. In fact, 81 of them sold PPE (61.8%), 54 sold medicines (41.2%), 20 sold medical frauds (15.3%), 9 sold tests (6.9%), and 2 sold ventilators (1.5%). The information in this paragraph is summarized in Table 8.

It is important to note that vendors often do not provide complete information on their listings but rather invite direct communication. In 403 (77.8%) unique listings, the vendor invited potential customers to communicate via email or messaging applications like WhatsApp, Wickr Me, and Snapchat. Thus,
Table 3: Summary statistics for the considered categories of listings. For each category, we included the number of unique listings, observations, and vendors. If the same vendor sold listings in different categories, we counted it as one unique vendor.

| Category        | Unique listings | Total observations | Vendors |
|-----------------|-----------------|--------------------|---------|
| PPE             | 343 (66.2%)     | 5,536 (77.3%)      | 81 (61.8%) |
| Medicines       | 132 (25.5%)     | 1,276 (17.8%)      | 54 (41.2%) |
| Medical Frauds  | 31 (6.0%)       | 235 (3.3%)         | 20 (15.3%) |
| Tests           | 10 (1.9%)       | 34 (0.5%)          | 9 (6.9%)  |
| Ventilators     | 2 (0.4%)        | 78 (1.1%)          | 2 (1.5%)  |
| COVID-19        | 518 (100%)      | 7,159 (100%)       | 131 (100%)|

478 (92.3%) COVID-19 specific listings contained no information about the offered amount of goods, 408 (78.8%) did not provide shipping information, and 13 (2.5%) did not disclose the listing price.

The median price of PPE was 2 USD and they were the least expensive products, followed by medicines with 34 USD, tests with 70 USD, medical frauds with 200 USD, and ventilators with 1,400 USD. The distribution of prices for these categories can be found in Figure 2(a), showing that many listings had a low price around a few USD or less and only few listings exceeded thousands or more USD. The cumulative value of the detected unique listings is 531,413 USD, where we excluded listing with prices larger than 40,000 USD due to manual inspection. When vendors post listings at high price this typical indicates they have halted sales of an item with the expectation of selling it again in the future.

We remove these anomalously high priced listings since they would largely overestimate the sales price of the actually active listings.

The shipping information declared in the analysed listings involved a total of 12 countries or regions. Most of the vendors are willing to ship worldwide. Shipping from different continents is possible because some vendors explicitly declare that they have multiple warehouses across the globe, while shipping to any continent is done through specialized delivery services. The United States is the second largest exporter and shipping destination. Germany is the third largest exporter but no vendors explicitly mentioned it as a shipping destination. Complete shipping information is available in Figure 2(b). Some examples of the COVID-19 specific listings are available in the Appendix B.1.

Figure 3(a) presents a word cloud built from the titles of the selected COVID-19 specific listings. The wordcloud was built from 1-grams, meaning single words, excluding common English words and stop words. It illustrates that DWM vendors were particularly aware of the worldwide need of face masks because “face mask” were the most used words in the selected COVID-19 specific listings. The COVID-19 pandemic was referred to as either “coronavirus,” “corona,” “covid,” or “covid19.” Interestingly, we did not find any mention about the word “pandemic” itself. Among COVID-19 medicines, “hydroxychloroquine” and “chloroquine” were the most popular ones, with fewer mentions of “azithromycin,” “medicated,” and “medical” products in general.

DarkBay/DBay contained the majority of the COVID-19 specific listings in our dataset, amounting to 421 (81.3%). The most available unique listings in DarkBay/DBay were PPE, which totaled 291. We also found 103 medicines, 24 medical frauds, 1 tests, and 2 ventilators. The number of listings available in the other marketplaces was: 33 in Yellow Brick, 19 in DarkMarket, 2 in Connect, 33 in Empire, 3 in The Canadian HeadQuarters, and 5 in White House, as shown in Table 2. The entire breakdown of the number of COVID-19 specific listings detected in each category is available in Figure 3(b).

In Figure 3(c), we ranked the marketplaces for their share of vendors selling COVID-19 specific listings. The total number of vendors behind COVID-19 specific listings in our dataset is 131. Most
Figure 2: (a) Box plot of the distribution of listing prices for each COVID-19 category. The box ranges from the lower to the upper quartile, with the horizontal line indicating the median. The whiskers extend up to the 5th and 95th percentiles respectively. The dots represent outliers. (b) Shipping information in COVID-19 specific listings. Note that 408 (or 78.8%) of these listings did not provide any shipping information.

Figure 3: (a) Word cloud for “Listing title” in COVID-19 specific listings. (b) Category breakdown of COVID-19 specific listings in the specific marketplace that offered them. (c) Fraction of vendors selling at least one COVID-19 specific listing. (d) Vendor specialisation. Most vendors responsible for at least one COVID-19 specific listing also sell other listings, and in greater numbers.
19 specific listings. In Appendix [D], we analysed the distribution of COVID-19 specific listings for each vendor. We found that it was heterogeneous according to a power-law with an exponent equal to $-2.0$ and 80% of the vendors had less than 5 listings, as shown in Figure [7]. In DarkBay/DBay, more than 10% of the vendors were selling COVID-19 specific listings, while in Empire, The Canadian Headquarters, and White House this fraction was fewer than 1%. Finally, Figure [5(d)] shows that essentially no vendors specialised on COVID-19 products, with only 6 vendors selling more COVID-19 specific listings than unrelated ones, 4 of which actually sold just one COVID-19 specific listing overall in our dataset.

**Time evolution of DWM listings and public attention**

The number of active unique listings evolved over time, as shown in Figure [4(a)]. The first COVID-19 specific listing in our dataset appeared on January 28, 2020, following the Wuhan lockdown[1]. In March 2020, lockdowns in many countries[59, 60] corresponded to an increase in the number of these listings, whose number kept increasing until May 2020. In June and July 2020, when worldwide quarantine restrictions started to ease[61], we observed a decreasing trend in the selected COVID-19 specific listings. Figure [4(b)] shows the evolution of the total number of observed PPE and medicines, the two most available COVID-19 specific listings in our dataset (see Table [3]). PPE followed a trend compatible with the overall observations shown in Figure [4(a)], with a peak in May 2020 and a decrease afterwards, while COVID-19 medicines remained approximately stable from April 2020.

The time evolution of the listing prices followed a different pattern. We considered the median price and its 95% confidence interval of active COVID-19 specific listings in Figure [4(c)], and of active PPE and medicines, in Figure [4(d)]. Initially, the only COVID-19 specific listings concerned medicines and specifically azithromycin, already sold on DWMs before the pandemic as an antibiotic. These listings were not observed in the first part of March. Medicines reappeared in DWMs the week after the President of the United States Donald Trump first mentioned chloroquine[62]. Their median price was stable for the remaining time period under consideration. PPE listings appeared for the first time in March 2020. The median price of PPE was high for March and most of April, possibly due to speculation. Interestingly, at the end of April, a vendor named “optimus,” active on DarkBay, started selling large quantities of PPE at 1 USD, putting many online listings at the same time, thus drastically reducing the median price, which remained low until July. Overall, “optimus” had 91 PPE listings during the registered period.

We also considered tweets and Wikipedia page visits as proxies for public attention. We focused our analysis on the PPE category and on the three most present medicines in our dataset: hydroxychloroquine, chloroquine and azithromycin. Figure [5(a)] shows that a first peak in public attention on PPE was reached in late January 2020 following the Wuhan lockdown[1] and a second peak in March 2020[53] when PPE listings started to appear in DWMs. The number of PPE listings reached their maximum in May 2020. After May, PPE listings steadily decreased along with public attention. It is worth noting that May also marked the end of the “first wave” of contagion in many European countries[64]. The last peak detected for the number of tweets in the beginning of July might be caused by the introduction of a new methodology to collect tweets in the freely available dataset we considered[22].

A similar relationship between mass media news, public attention, and DWMs was registered for the listings regarding the three considered medicines, as shown in Figures [5(b) and (d)]. Three peaks in public attention were detected after three declarations from President Trump about these medicines[62, 65, 66] and the number of active medicines listings closely followed. However, a closer look reveals the different shapes of the Wikipedia page visits, tweets, and DWMs curves. Wikipedia saw a very high peak of page visits.
after the first declaration from President Trump, and smaller peaks in correspondence in the following declarations. Tweets instead saw peaks of attention of increasing height. DWM listings on the contrary were much steadier in time and with little variation in the number of active listings.

Figure 5: DWMs and public attention. (a)-(c) Seven-days rolling average of active listings selling PPE, together with the time evolution of the number of tweets referring to masks and of visits in the relative Wikipedia page visits. (b)-(d) Similar comparison as in panels (a)-(c) but considering active listings of hydroxychloroquine, chloroquine, and azithromycin. Black dashed vertical lines in panels (a) and (b) mark significant events related with COVID-19, see Appendix C. See Appendix D for panels (a) and (b) with a linear y-axis.
Impact of COVID-19 on other listings

We considered the indirect impact of COVID-19 on all the 23 DWMs in our dataset by looking at listings mentioning lockdown, using keywords “lockdown” or “quarantine,” delay, using “delay” or “shipping problem,” and sales, using “sale,” “discount,” or “special offer.” Examples of listings reporting these keywords are available in Appendix B.2.

Figure 6(a)-(b)-(c) shows the percentage of listing in time mentioning these themes, considering the full dataset. The percentage of all listings in the 23 DWMs mentioning lockdown never exceeded 1% and reached its maximum in late April only, when many lockdown measures were adopted\cite{1,59,60}, as illustrated in Figure 6(a). Delay mentions reached their peaks in March, April, and May, after major COVID-19 events, such as lockdowns\cite{59,60} one million worldwide cases\cite{67} and the situation in Europe starting to improve\cite{64}, respectively, as shown in Figure 6(b). A similar pattern was visible for the percentage of all listings mentioning sales. In addition, we observed that sales had a first peak corresponding to the New Year, which is a common practice of many in-person legal shops, as displayed in Figure 6(c). Interestingly, despite observing that the increase in the percentage of all listings mentioning sales, delays, and lockdown followed major events related to the pandemic, not all of these listings also mentioned COVID-19. We further researched this by plotting which percentage of the relative listings also mentioned COVID-19 in Figure 6(d). The percentage of listings mentioning that the current sales were due to COVID-19 was less than 1%, while mentions of delays reached up to 40%. For lockdown it was 100%, as one can expect since lockdowns exist because of COVID-19. In the three selected cases, the percentages of listings mentioning COVID-19 increased in time, following the global awareness about the current pandemic.

![Figure 6: Percentage of all active listings mentioning the themes lockdown, delay and sales in panels (a), (b), (c), respectively. (d) Percentage of active listings in panels (a), (b), (c) that also mentioned COVID-19 in their listings. Black dashed vertical lines in panels (a), (b), and (c) corresponded to major COVID-19 events, see Appendix C.](image-url)
Conclusion and discussion

In summary, we investigated the presence of listings related to COVID-19 in 23 DWMs, monitored over a six-month period in 2020. We considered COVID-19 mentions and COVID-19 specific listings, finding them in 12 and 7 DWMs, respectively. COVID-19 specific listings totaled 518 and represented less than 1% of our dataset. The majority of COVID-19 specific listings offered PPE (66.2%), followed by medicines (25.5%), medical frauds (6.0%), tests (1.9%), and ventilators (0.4%). Most COVID-19 specific listings did not report the quantity sold (92.3%) or shipping information (78.8%), and invited potential customers to communicate via email or messaging applications, like WhatsApp (77.8%). Direct communication fosters a trustworthy vendor-buyer relationship and may lay the ground for future tradings outside DWMs. However, they expose users to higher risks of being traced by law enforcement.

In our dataset, DarkBay/DBay is featured prominently among marketplaces offering COVID-19 specific listings. Ranking in the top 100 sites in the entire dark web, DarkBay/DBay is regarded as the eBay of the dark web because it offers more listings categories than other DWMs. It was also frequently accessible during the period of time monitored during this research, with an uptime of 86% during this period, higher from the 77% uptime of Empire, the largest marketplace at the time of writing.

Our work corroborates previous findings and expands on them in several ways. The most extensive report to date, to the best of our knowledge, examined the presence of COVID-19 specific listings in 20 DWMs on one single day (April 3, 2020). Despite a small subset of overlapping marketplaces between that report and our study, we both assessed that COVID-19 specific listings constituted less than 1% of the total listings in the DWM ecosystem. These listings were mostly PPE, followed by medicines and they were found in only a few DWMs, while non COVID-19 specific listings were widespread.

An important novelty of the present study, compared to the existing literature, is the analysis of the temporal evolution of DWM behaviour and its relationship to public attention, as quantified through tweets and Wikipedia page visits. Following the Wuhan lockdown, we observed a first peak in the public attention, and a corresponding emergence of the COVID-19 specific listings. A second peak in public attention occurred in March 2020, when quarantine measures were adopted by many European countries. Again, during the same period, the number of COVID-19 specific listings sharply increased. Finally, when worldwide quarantine began to ease in many countries, in June and July 2020, we registered a decrease in public attention and in available COVID-19 specific listings.

Listing prices correlated with both variations in public attention and individual choices of a few vendors. Median price experienced a sharp increase in March 2020, probably due to speculation, and then decreased in April due to the choice of a single vendor responsible for 91 listings, named “optimus.” The vendor sold a large quantity of PPE at 1 USD only, which constituted the 37% of active PPE listings in April 2020. Finally, we observed an increase in the percentage of all listings citing delays in shipping and sale offers, which peaked in March, April, and May 2020. Similar to a prior work that found Wikipedia page visits of a given drug to be a good predictor for its demand in DWMs, we provide further evidence that the DWM ecosystem is embedded in our society and behaves organically to social changes. The DWM ecosystem swiftly reacted to the pandemic by offering goods in high demand, and even tried to fulfill desires through evident scams, for example by offering vaccines already in March 2020, when no tested vaccination existed.

Our research shares some limitations with previous studies, namely that not all active DWMs were
surveyed. For instance, we did not analyse 15 of the marketplaces explored in the previous report. \cite{19} It must be noted, however, that the number of active marketplaces is constantly changing due to closures or new openings, \cite{19} and obtaining full coverage is challenging due to the active efforts of DMWs to obstruct research studies and law enforcement investigations, for example through the use of CAPTCHAs.

By revealing that DWMs listings of goods related to COVID-19 exist and that they are correlated with public attention, we highlight the need for a close monitoring of the online shadow economy in the future months. For example, we expect that initial delays in the availability of a cure and/or vaccine would dramatically increase public interest for the online shadow economy, posing concrete risks to public health. We plan to improve our analysis of DWM activity by increasing the number of monitored DWMs and conducting a more extensive analysis of the impact on the pandemic on overall DWM trade by considering changes in prices of non-COVID-19 specific listings, such as drugs, weapons or malware. We anticipate that our results and future work will help inform the efforts of public agencies focused on protecting consumer rights and health.\cite{24}

Competing interests

The authors declare that they have no competing interests.

Author’s contributions

A.Ba., A.T. and A.G. conceived of the project. A.Ba. coordinated the project. All authors designed the research. M.A. and I.G. provided the data. A.Br., M.N., M.A. and I.G. preprocessed and analysed the data. All authors analysed the results. A.Br., M.N., and A.Ba. wrote the manuscript. All authors read and commented on the manuscript.

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Correspondence

Correspondence and requests for materials should be addressed to Andrea Baronchelli: Andrea.Baronchelli.1@city.ac.uk.

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The COVID-19 online shadow economy

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A Data pre-processing

In the following, we describe the DWMs dataset in more details, by focusing on how listings were stored and how we formed the COVID-19 categories in table 1, that is, PPE, medicines, medical frauds, tests, ventilators, and COVID-19 mentions.

Table 4: Selected attributes of the listings under consideration along with a brief explanation of their respective purposes.

| Attribute of a listing  | Explanation                                                                 |
|------------------------|-----------------------------------------------------------------------------|
| “Listing body”         | Description of the listing as it appears in the DWM                         |
| “Listing title”        | Title of the listing as it appears in the DWM                              |
| “Marketplace name”     | Name of the DWM                                                             |
| “Shipping information” | Where the listing is declared to ship from and to                          |
| “Time”                 | When the listing is observed                                                |
| “Quantity”             | Quantity of the listing sold                                                |
| “Price”                | Price of listing                                                            |
| “Vendor”               | Unique identifier of the vendor                                             |

The listings appearing on the DWMs were crawled and stored according to selected attributes. While a brief explanation of these attributes is already presented in table 4, here we focus on those attributes which involved some pre-processing before the analysis, that is, “Shipping information,” “Quantity,” and “Price.” The “Shipping information” attribute was initially stored considering what the vendor declared. Then, it was standardised among vendors to correct any misspellings, using the standard python library `pycountry`. Vendors may declare a specific country, like United States, a continent, like Europe, or the entire world, which we standardise here as worldwide. The “Quantity” attribute was instead retrieved from the title of the listing using Facebook open-source library `Duckling`, then it was manually checked and corrected during an annotation process. The “Price” attribute on DWMs was displayed in the listings in various currencies, such as cryptocurrencies and fiat currencies. In order to standardise and properly compare listing prices, we converted prices to USD at the daily conversion rate. Rates were taken from Cryptocompare for cryptocurrencies, and from the European Central Bank for fiat currencies.

The attributes “Listing body” and “Listing title” in table 4 representing the title and description of the listings, were used to select the COVID-19 categories in table 1. To this end, we prepared two sets of keywords as shown in Table 5. Every selected COVID-19 listing contained either a word in the “Listing body” that matched one keyword in the first set or a word in the “Listing title” that matched one keyword in the second set. The rationale behind this choice was that the listing title was usually more precise on the product sold, whereas the body might contain promotions of other items the vendor was selling in other listings. At the same time, the vendor might mention COVID-19 in the body for various reasons, which we analysed in the main text. In order to classify listings in either COVID-19 specific listings (that is, PPE, medicines, medical frauds, tests, ventilators) or COVID-19 mentions, we ran a regex query in google bigquery. We remark that the chosen method returned words containing a string equal to one of our keywords. For instance, with the keyword chloroquin, we detected also chloroquine and hydroxychloroquine. After this automatic filtering step, we manually checked the selected COVID-19 related listings to further improve the accuracy of our sample. In order to minimize human error, at least two authors of the present manuscript checked each of these listings. A limitation of our approach was that keywords considered were in English. Therefore, even if drug names such as chloroquine were
common to many languages and we detected some listings in a non-English language, our sample of COVID-19 related listings was biased toward the English language.

Table 5: Keywords used to sample COVID-19 specific listings from the DWMs in table 2

| First set of keywords checked against the words included in the attribute “Listing body” in table 4 |
| corona virus, coronavirus, covid, covid-19, covid19 |

| Second set of keywords checked against the words included in the attribute “Listing title” in table 4 |
| anakinra, antidote, antiviral, azithromycin, baloxavir, baricitinib, bemcentinib, chloroquin, corona virus, coronavirus, covid, covid-19, covid19, darunavir, dexamethason, diagnosis, diagnostic, favipiravir, ganciclovir, glove, gown, lopinavir, marboxil, mask, n95, n99, oseltamivir, prevention, remdesivir, repurposed, ribavirin, ritonavir, sanitiser, sanitizer, sarilumab, siltuximab, surgical, thermo scanner, thermo-scanner, thermometr, thermoscanner, tocilizumab, umifenovir, vaccine, ventilator |

While each listing had an associated url to determine its uniqueness, which allowed us to track listing over time, vendors receiving bad reviews sometimes put identical copies of the same listing online. To overcome this issue and correctly count the number of listings, we determined a listing as unique if it had the combination of “Listing body,” “Listing title,” “Marketplace name,” and “Vendor” different than any other listings. For instance, if two listings had the same title and body but were sold in two different marketplaces, we considered them as two different listings. Also, we considered at most one observation for each unique listing per day. The total number of unique listings and observations of these listings in each DWM is available in table 2.

B Examples of listings related with COVID-19 in dark web marketplaces

Here, we present detailed examples of the selected listings. We consider both COVID-19 specific listings and COVID-19 mentions.

B.1 COVID-19 specific listings

The most popular category of COVID-19 specific listings was PPE, which included mainly face masks. We detected that 91% of listings did not specify the amount of masks sold. Within those who declared the amount sold, we found listings selling small quantities of masks, like “KN95 Face Mask for Corona Virus box of 50” priced at 50 USD, while others proposed wholesale deals, as in “AFFORDABLE 20 BOXS OF SURGICAL FACE MASK (WHOLESALE PRICE)” in which 5000 masks were available at 2,000 USD.

The second most popular COVID-19 category was medicines, composed mostly by chloroquine, hydroxychloroquine, and azithromycin. Like PPE, 84% of the times vendors did not specify the quantity sold. When they did, it usually was for wholesale deals, as in “9000 tabs hydroxychloroquine 200mg (USA AND CANADA ONLY)” where 9,000 tabs were sold for 1,194 USD. The smallest quantity we detected was 50 pills “chloroquine 50pills for 250$,” sold at 250 USD. We also noticed that vendors often specified the size of the pill, being it 200mg, 250mg, or 500mg. The azithromycin was usually sold together with hydroxychloroquine as a prescription against COVID-19. One example of it was “hydrox-
ychloroquine sulfate 200mg and azithromycin 250mg,” where an unknown quantity of these drugs was sold for 40 USD.

In the COVID-19 category of medical frauds, the most prominent listings were vaccines. Despite at the moment of writing of this manuscript (July 2020), vaccines are far from being actually developed, they were sold in DWMs since March 2020. These listings included both low price vaccines like “complete order free shipment COVID19 VACCINE,” sold at just 200 USD, or high price one like “Covid-19 Vaccine. Lets keep it low key for now,” priced at 15,000 USD. In addition, among the listings in the medical frauds category, one could find potentially dangerous illicit drug mixes with claimed curative power against COVID-19, like “Protect yourself from the corona virus:” a marijuana based drug mix supposedly helpful in recovery from coronavirus infection. Other medical frauds included a 300 USD “CORONAVIRUS DETECTOR DEVICE, SAVE LIVES NOW” or a 1,000 USD “Buy CORONAVIRUS THERMO METER.”

Tests for COVID-19 were also moderately present in DWMs during the pandemic. We detected listings in the tests category both at low quantities, such as, “25 pcs COVID-19 (coronavirus) quick test,” sold for 430 USD, or at very large one, like “Corona Virus Test / Covid-19 Test Kits (5000Pcs),” for a price of 7,500 USD.

The two listings in the ventilator category were ICU ventilators. They were advertising fundamental hospital instrument, such as, “ICU Respiratory Ventilators, Emergency Room Vents” sold at 800 USD or “BiPAP oxygen concentrator ventilator Amid Covid-19” for 2,000 USD.

B.2 COVID-19 mentions

We describe three examples of listings in the COVID-19 mentions category. The listing with title “Best Organic Virginia Bright Tobacco Premium quality 600g” refers to the lockdown in its body as “unfortunately we have to respect coronavirus lockdowns, in order to ensure as much security as possible, we had to choose one type of shipping that is unfortunately much more expensive while lockdows last.” Another listing with title “[Out of Stock! Lower Price for Pre-orders Only] Testosterone Enanthate 250mg/ml - 10ml - Buy 4 Get 1,” mentions in the body that they “are currently out of stock of this product due to our oil suppliers not being able to get their raw powders shipped to them because of the Coronavirus” and they “have lowered the price a little to help make up for this delay.” A third listing mention a sale directly in the title “COVID-19 SPECIAL OFFER 1GR CROWN BOLIVIAN COCAINE 90% 65,” and link the discount with the distress caused by the pandemic.

C Timeline of the COVID-19 pandemic

In this Section we aim at providing a summary of the main events related to the pandemic, focusing on the ones cited in the main text and listed in table 6. This is by no means a complete summary of the COVID-19 pandemic timeline.

The first event to gain international attention and make the public aware of the coronavirus was the decision from China to lockdown the city of Wuhan, first epicenter of the pandemic, on the January 23 2020. The virus then found its way to Europe, where the first country to be heavily hit by the pandemic was Italy. The Italian government decided to lockdown the entire country on March 9 2020. The virus rapidly spread in Europe and internationally, with cases appearing more and more in the...
United States, leading USA’s President Donald Trump to first take a stance on the possibility of using chloroquine to cure individuals infected from COVID on the March 18 2020. The epidemic started to heavily hit the United States, with New York City declaring the lockdown on March 22 2020 and the cases were surging almost everywhere in the world: 70 days after the lockdown of Wuhan, the worldwide count of infections had already surpassed 1 Million cases on April 3 2020. At that point, President Trump explicitly promoted the use of hydroxychloroquine on April 5 2020, before any official medical trial ended. In April the situation started to become asymmetric. In Europe, thanks to the many policies in place, the COVID-19 became less threatening and lockdowns started to be eased. USA and other countries were instead seeing a rise in cases. President Trump declared he was now taking Hydroxychloroquine preventively against COVID-19 on May 18 2020 and the USA were the first to register 100,000 deaths on May 27 2020. During June 2020, Europe has maintained COVID-19 under control, while the USA is having a second wave in cases related with COVID-19.

Table 6: Significant COVID-19 events. We defined an acronym for each event and reported it in the main text plots. Please note that this list does not intend to be exhaustive or to establish a ranking between events.

| Date       | Event                                                                 | Acronym     |
|------------|-----------------------------------------------------------------------|-------------|
| 2020-1-23  | Wuhan Lockdown                                                        | Wuhan       |
| 2020-3-9   | Italy Lockdown                                                        | Italy       |
| 2020-3-18  | USA’s President Trump first refers to chloroquine                     | Trump 1     |
| 2020-3-22  | New York City Lockdown                                                | NYC         |
| 2020-4-3   | 1M COVID-19 cases worldwide                                           | 1M cases    |
| 2020-4-5   | USA’s President Trump promotes the use of chloroquine and hydroxychloroquine against COVID-19 | Trump 2     |
| 2020-4-24  | COVID-19 cases in Europe are beginning to slow down                   | Europe      |
| 2020-5-18  | USA’s President Trump declares he is taking hydroxychloroquine         | Trump 3     |
| 2020-5-27  | 100k COVID-19 deaths in the USA                                       | 100k USA deaths |

D Supplementary material

In this Section we provide additional material that support our main findings. In table 7 we provide more details on the 23 dark web marketplaces considered in our study. In particular we indicate the main specialization of the markets, i.e., the main category of products sold. If it is “Mixed”, it means that the marketplace is not specialised in any particular category of goods. In the description we instead put information on the markets, with more details where available. All this information has been researched and compiled by the authors, with particular help given by Flashpoint Intelligence.

In table 8 we provide a table reporting the different COVID-19 related medicines which were found in the listings. The medicines were selected as they have been found or claimed to be effective against COVID-19. The number of listings related to each medicine is also reported, noting that some listings sell more than one medicine (e.g. listings selling both hydroxychloroquine and azithromycin).

In figure 7 we plot the distribution of listings per vendor in log-log plot, showing a clear power-law shape with exponent -2.0. In the inset of figure 7 we show the histogram using linear spacing, through which we understand that most vendors sold very few COVID-19 specific listings, while few vendors going as high as 91 different listings. We noted that 80% of the vendors had indeed less or equal than 5 listings.
In order to complement figure 5(a) and (b) in the main text and properly show the peaks of Wikipedia page visits and tweets, we create figure 8. The new representation of figure 5 does not modify the claims made in the main text and how major event related with COVID-19 impacted public attention.

Table 7: List of all dark web marketplaces, together with their specialization and a brief description.

| DWM                     | Specialization | Description                                                                 |
|-------------------------|----------------|-----------------------------------------------------------------------------|
| Black Market Guns       | Weapons        | Weapons Marketplace, now exit scammed according to onion.liv[35]            |
| CanadaHQ                | Mixed          | Multivendor cryptocurrency marketplace                                       |
| Cannabay                | Drugs          | Russian language drug marketplace focusing on cannabis                      |
| Cannazon                | Drugs (Cannabis)| Drug marketplace for cannabis products only                                  |
| Connect                 | Mixed          | A social network that hosts a marketplace for the sale of illicit goods       |
| DarkBay/DBay            | Mixed          | Multivendor cryptocurrency marketplace selling digital goods, drugs, and services |
| Dark Market             | Mixed          | Multivendor cryptocurrency marketplace selling digital goods, drugs, and services |
| Darkseid                | Weapons        | Weapons marketplace                                                         |
| ElHerbolario            | Drugs          | Single-vendor shop, selling just 3 products, primarily leaning towards Cannabis|
| Empire                  | Mixed          | Alphabay-style marketplace with BTC, LTC, XMR, MultiSig, and PGP 2FA         |
| Genesis                 | Digital goods  | Marketplace selling digital identities for account takeover activities        |
| Hydra                   | Drugs          | Russian language drug marketplace                                           |
| MEGA Darknet            | Mixed          | Russian language marketplace                                                |
| Plati.Market            | Digital goods  | digital goods marketplace                                                    |
| Rocketr                 | Digital goods  | Marketplace for the sale of illicit digital goods                           |
| Selly                   | Digital goods  | Marketplace for the sale of illicit digital goods                           |
| Shoppy.gg               | Digital goods  | Marketplace for the sale of illicit digital goods                           |
| Skimmer Device          | Skimmer devices| Marketplace selling skimmer devices                                         |
| Tor Market              | Drugs          | Drug-focused marketplace focused on supplying the drug marketplace in New Zealand |
| Venus Anonymous         | Mixed          | Multivendor marketplace selling digital goods and drugs                      |
| White House             | Mixed          | Multivendor cryptocurrency marketplace                                       |
| Wilhaben                | Mixed          | German language marketplace for the sale of illicit goods                    |
| Yellow Brick            | Mixed          | Multivendor cryptocurrency marketplace                                       |
Table 8: COVID-19 related medicines appearing in the listings, together with a brief description and the number of listings related to that drug.

| Medicine       | Description                                           | Listings |
|----------------|-------------------------------------------------------|----------|
| Chloroquine    | Malaria medication                                   | 59       |
| Hydroxychloroquine | Malaria medication                               | 56       |
| Azithromycin   | Antibiotic often paired with hydroxychloroquine      | 30       |
| Favipiravir     | Antiviral medication used to treat influenza         | 5        |
| Remdesivir     | Antiviral medication                                | 3        |
| Lopiravir      | Antiviral medication used to treat HIV               | 1        |

Figure 7: Probability distribution function (Pdf) for the number of listings per vendor. The power law fit results in an exponent of -2.0. In inset, the histogram of the number of listings per vendor, with a vertical line showing the 80th percentile.
Figure 8: Wikipedia page visits for pages relative to (a) PPE, (b) hydroxychloroquine, chloroquine and azithromycin. Number of tweets mentioning (c) PPE, (d) hydroxychloroquine, chloroquine and azithromycin. Panels (a) and (b) corresponds to figure 5(a) in the main text, while panels (c) and (d) to figure 5(b). The main difference between these panels and figure 5(a) and (b) is the linear scale on y axis.