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Bitcoin, gold and the US dollar – A replication and extension

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ABSTRACT

Dyhrberg [2016. Bitcoin, gold and the dollar – A GARCH volatility analysis. Finance Research Letters 16, 85–92] analyzes the relationship between Bitcoin, gold and the US dollar and states that Bitcoin can be classified as something in between gold and the US dollar. This paper uses the same sample and econometric models to replicate the findings and demonstrates that exact replication is not possible and that alternative statistical methods provide more reliable, yet very different results. The findings based on the original sample and an extended sample period show that Bitcoin exhibits distinctively different return, volatility and correlation characteristics compared to other assets including gold and the US dollar.

1. Introduction

Replication studies are rare in economics and finance despite evidence that such studies stimulate academic rigor and enhance the reliability of published research De Vita and Trachanas (2016). In our view, a replication study of Dyhrberg (2016) "Bitcoin, gold and the dollar – A GARCH volatility analysis" is one step towards more replication studies in economics and finance. Using GARCH models, Dyhrberg (2016) aims to study if and which (statistical) properties Bitcoin shares with gold and currencies. We will illustrate that the employed econometric models are misspecified both in econometric and in economic terms as the model cannot help to answer the research question proposed. Consequently, the interpretations and conclusions are misleading.

Since Dyhrberg (2016) research questions are well motivated and important, we do not only intend to replicate her results but also extend the sample and use an alternative framework to analyze these questions. We propose that a descriptive analysis is sufficient to answer the main question. Furthermore, such an analysis is an important benchmark for seemingly more "sophisticated" approaches such as GARCH models to identify distinguishing characteristics of the volatility processes of Bitcoin, gold, currencies, and equity returns.

The extreme increase of Bitcoin's market value on the one hand and its limited usability as a means of payment on the other hand lead to the question whether Bitcoin is an investment asset, a gold-like store of value, or a currency (cp. Bell, 2013; Glaser et al., 2014). If Bitcoin has the potential to become a globally accepted medium of exchange and thus the equivalent of established fiat currencies such as the US dollar or the euro, this may have disruptive consequences for central banks, monetary policy, the value of fiat currencies and the world economy in general. However, Fig. 1 shows that Bitcoin is unlike any other major asset class. The price path of Bitcoin has been very volatile since its introduction. In particular, its volatility is decisively higher than volatility of gold, the US dollar, or stock markets (represented by the MSCI World Index).

Fig. 2 presents the return time series of the respective assets and reinforces this statement as the dispersion of Bitcoin returns is

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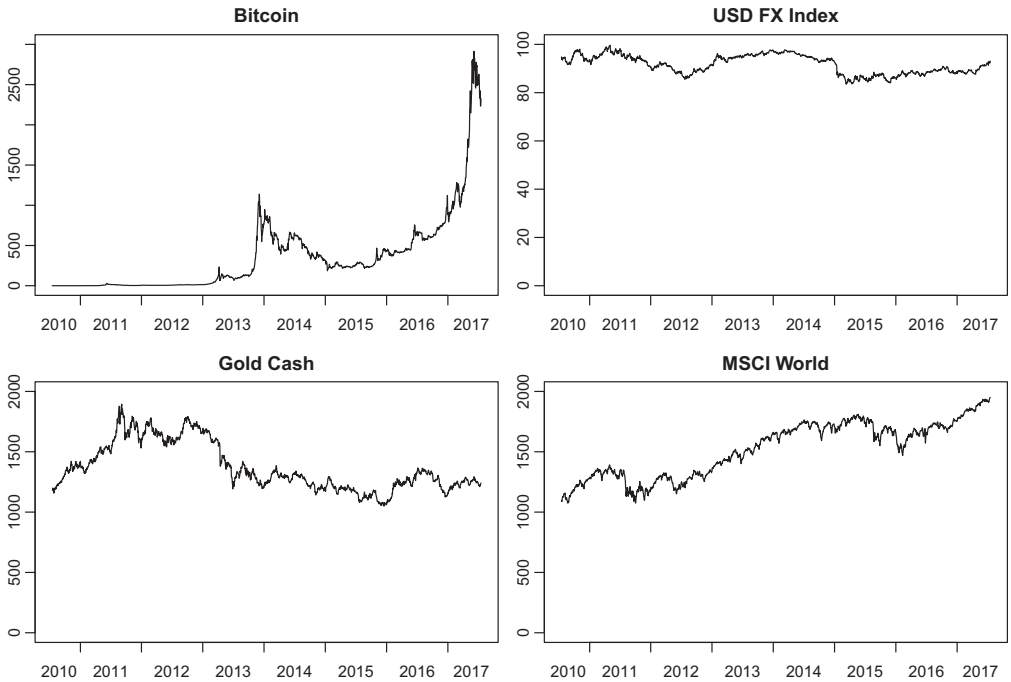

Fig. 1. Bitcoin, USD FX Index, Gold and MSCI World.

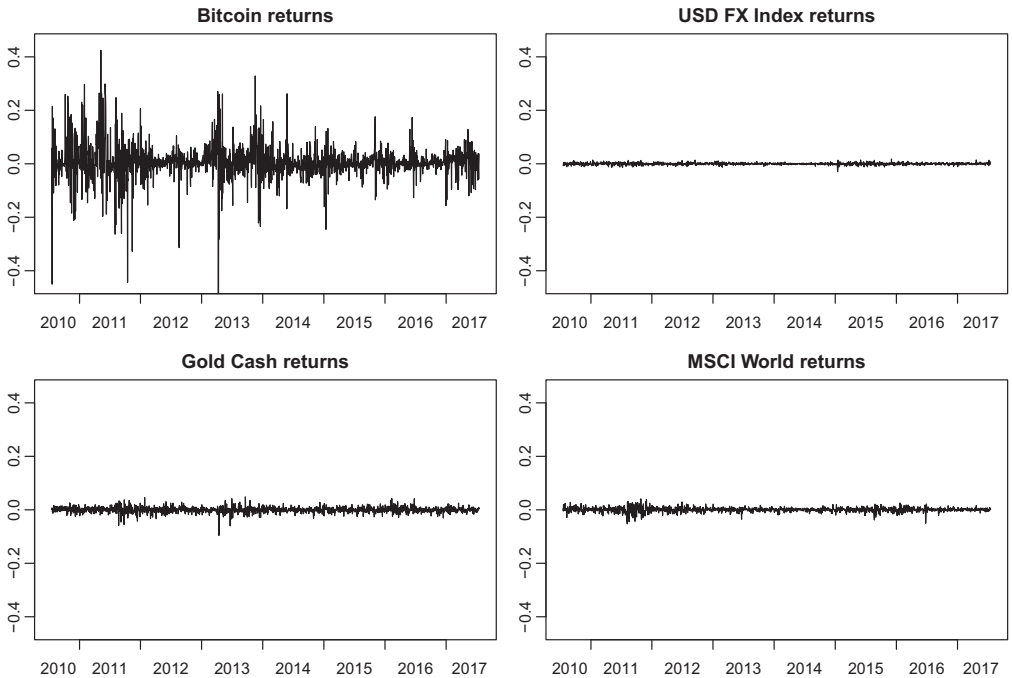

Fig. 2. Bitcoin, USD FX Index, Gold and MSCI World Returns.

about 10 times higher than the one observed for gold, the US dollar, or the MSCI world index.

Observing very different price paths may be surprising given that Bitcoin's design shares key features with gold (mining, decentralization, not government-backed, globally traded 24 hours a day, 7 days per week) and currencies (medium of exchange) (Dwyer, 2015, cp.). Selgin (2015) argues that Bitcoin is a synthetic commodity money as it resembles commodity money (e.g. gold) in being not just contingently but absolutely scarce and it resembles fiat money (e.g. the US dollar) in having no intrinsic value.

These considerations highlight the importance of the research question proposed by Dyhrberg (2016), namely how Bitcoin behaves compared to gold and the US dollar and more specifically, "[...] if bitcoin behaves like a well-known asset or as something in

between a commodity and a currency [...]" (page 86). A comparative empirical analysis of Bitcoin's characteristics with different forms of money (commodity and fiat) and other asset classes (equity and cash) is informative as there is disagreement about the key function of Bitcoin (e.g. Whelan, 2013). The main difference between standard currencies and Bitcoin is that the former are backed by sovereign governments Goodhart (1998) while Bitcoin is not. The underlying blockchain technology (Böhme et al., 2015) reduces the need for a central third-party institution to serve as authorities of trust.

To answer her research question, Dyhrberg (2016) relies on a GARCH approach. In the following, we first implement a replication of her models. In a second step, we demonstrate that the employed GARCH models do not and cannot provide an answer to the research question. We therefore propose an alternative approach to analyze if Bitcoin behaves like a well-known asset or something in between a commodity and a currency. In contrast to Dyhrberg (2016) we study returns and return volatility separately for each asset class. This allows us to examine the statistical properties of each asset to compare them across assets. These new results are plausible and consistent with the existing literature (e.g. Yermack, 2013), yet in stark contrast to the findings in Dyhrberg (2016).

The paper is structured as follows. Section 2 describes the data set, the econometric framework and the main findings reported in Dyhrberg (2016). We present the best replication attempt and provide explanations why we failed to exactly replicate the findings. Section 3 presents an alternative framework to analyze the main research questions. Section 4 summarizes and concludes.

2. Replication

We use the same data and sample period (July 19, 2010 to May 22, 2015) as in Dyhrberg (2016). Bitcoin price data is downloaded from coindesk.com, all other variables are retrieved from Datastream. The sample consists of 1769 daily observations, including weekends since trading in Bitcoin is not confined to business days or the trading hours of stock exchanges. Since the remaining variables are not traded on weekends, Dyhrberg (2016) seems to assume zero returns for Saturdays and Sundays to align all time-series with the Bitcoin data.[1]

The variables and descriptive statistics are presented in Table 1 and are in line with the statistics reported in Dyhrberg (2016). Small differences stem from varying decimal places and rounding. The largest, albeit still small, differences are found for the mean of gold futures and gold cash.

Dyhrberg (2016) uses two GARCH models to "investigate the similarities between bitcoin, gold and the dollar" (page 87). Her GARCH(1,1) and EGARCH(1,1) models are specified as follows:

$$\begin{aligned}\Delta lnprice_t = \; & \alpha_0 + \alpha_1 lnprice_{t-1} + \alpha_2 lnprice_{t-2} + \alpha_3 Fed_{t-1} + \alpha_4 USDEUR_{t-1} \\ & + \alpha_5 USDGBP_{t-1} + \alpha_6 FTSE_{t-1} + \alpha_7 Gold\ Future_{t-1} + \alpha_8 Gold\ Cash_{t-1} + \varepsilon_t \end{aligned} \tag{1}$$

$$\begin{aligned}\sigma_t^2 = \; & \exp(\lambda_0 + \lambda_1 Fed_{t-1} + \lambda_2 USDEUR_{t-1} + \lambda_3 USDGBP_{t-1} + \lambda_4 FTSE_{t-1} \\ & + \lambda_5 Gold\ Future_{t-1} + \lambda_6 Gold\ Cash_{t-1}) + \alpha\varepsilon_{t-1}^2 + \beta\sigma_{t-1}^2 \end{aligned} \tag{2}$$

$$\begin{aligned}\Delta lnprice_t = \; & \alpha_0 + \alpha_1 lnprice_{t-1} + \alpha_2 Fed_{t-1} + \alpha_3 USDEUR_{t-1} + \alpha_4 USDGBP_{t-1} \\ & + \alpha_5 FTSE_{t-1} + \alpha_6 Gold\ Future_{t-1} + \alpha_7 Gold\ Cash_{t-1} + \varepsilon_t \end{aligned} \tag{3}$$

$$\begin{aligned}\ln(\sigma_t^2) = \; & \lambda_0 + \lambda_1 Fed_{t-1} + \lambda_2 USDEUR_{t-1} + \lambda_3 USDGBP_{t-1} \\ & + \lambda_4 FTSE_{t-1} + \lambda_5 Gold\ Future_{t-1} + \lambda_6 Gold\ Cash_{t-1} \\ & + \alpha(\varepsilon_{t-1}/\sigma_{t-1}) + \gamma(|\varepsilon_{t-1}/\sigma_{t-1}| - \sqrt{2/\pi}) + \delta \ln(\sigma_{t-1}^2) \end{aligned} \tag{4}$$

The models show how Bitcoin returns depend on lagged levels of Bitcoin[2], the lagged federal funds rate (in levels), lagged exchange rates (in levels), lagged equity and gold prices. In addition, the GARCH framework describes the volatility dynamics of Bitcoin. Since gold and US dollar exchange rates are covariates only, it is hard to see similarities between Bitcoin, gold and the US dollar. Moreover, since most of the covariates used by Dyhrberg (2016) are non-stationary I(1) variables (see the ADF test statistics reported in Table 1), the model is misspecified: both the mean and the variance equations require stationary exogenous variables (cp. Reinsel, 2003, Ch.8.1) to ensure stationarity of Bitcoin returns (the ADF test statistic in Table 1 implies stationarity). As the proposed model cannot be ergodic, both the coefficients and the variance estimates are not reliable. In addition, spurious correlation between the variables (in levels) might induce a severe multicollinearity problem.

While the motivation of using gold prices is obvious, the use of both spot and futures prices presents the problem that these variables are cointegrated and, hence, exhibit an extremely high correlation. The similarity of the coefficient estimates in magnitude albeit with different signs coupled with a high standard error (see Tables 2 and 3 in Dyhrberg (2016)) are indicative of this high correlation and a multicollinearity problem. Finally, it is not entirely clear why two different, non-nested GARCH models are used. Starting from the first model (cp. Eqs. (1) and (2)), the obvious extension that would include the asymmetric effect of positive and negative shocks in the variance equation would be the TGARCH model following Glosten et al. (1993).

[1] Dyhrberg (2016) is not explicit about the treatment of weekends. Hence, we calculated descriptive statistics both with the inclusion and the exclusion of weekends and found that only the former allows us to replicate the descriptive statistics.

[2] The actual models estimated in Dyhrberg (2016) use lagged Bitcoin returns. Estimations of models with lagged levels and alternatively lagged returns revealed that only the latter specification yielded results close to the estimates reported.

Table 1
Replication of Summary Statistics.

	Mean	SD	Min	Max	AR(1)	ADF
Bitcoin	170.31	240.13	0.05	1147.25	0.9970***	− 1.98
Ln(Bitcoin)	3.14	2.69	− 3.00	7.05	0.9986***	− 1.58
Bitcoin return	0.00	0.07	− 0.49	0.42	0.0281	− 15.04***
US Federal funds rate	0.12	0.04	0.04	0.21	0.9685***	− 2.96**
USD-EUR exchange rate	1.32	0.08	1.05	1.49	0.9987***	− 0.80
USD-GBP exchange rate	1.59	0.05	1.46	1.72	0.9916***	− 2.79**
FTSE 100 index	6151.00	523.07	4944.44	7103.98	0.9959***	− 3.59**
Gold futures	1441.38	194.24	1142.60	1889.00	0.9972***	− 1.58
Gold cash	1441.53	194.06	1146.00	1898.25	0.9973***	− 1.56
Observations	1769					

The table provides summary statistics for the sample period from July 19, 2010 to May 22, 2015 including weekends. Weekend returns are assumed to be zero for all assets except for Bitcoin. AR(1) provides the first order autocorrelation estimate. ADF provides *t*-statistics of an Augmented Dickey-Fuller test. *** (**, *) denotes significance at a 1% (5%, 10%) significance level.

Table 2
Replication of GARCH(1,1) with explanatory variables in mean and variance equation in Dyhrberg (2016).

Mean equation		
ΔLn(Bitcoin)$_{t-1}$	0.0775*	(2.54)
ΔLn(Bitcoin)$_{t-2}$	− 0.0131	(− 0.49)
US Federal funds rate$_{t-1}$	0.108**	(2.87)
USD/EUR FX return$_{t-1}$	0.0530**	(2.87)
USD/GBP FX return$_{t-1}$	− 0.0749*	(− 2.52)
FTSE 100 index$_{t-1}$	0.0000100**	(2.97)
Gold futures$_{t-1}$	0.000161	(0.98)
Gold cash$_{t-1}$	− 0.000142	(− 0.86)
Constant	− 0.0505	(− 1.11)
Variance equation		
Constant	− 4.205	(− 1.86)
α	0.276***	(16.61)
β	0.724***	(68.85)
US Federal funds rate$_{t-1}$	− 9.239***	(− 6.10)
USD/EUR FX return$_{t-1}$	12.78***	(10.33)
USD/GBP FX return$_{t-1}$	− 8.592***	(− 4.55)
FTSE 100 index$_{t-1}$	− 0.000625**	(− 2.91)
Gold futures$_{t-1}$	0.0176	(1.40)
Gold cash$_{t-1}$	− 0.0195	(− 1.56)
Observations	1767	

The table reports the estimation results of the best attempt to replicate the results in Table 2 of Dyhrberg (2016). Even though Eq. (1) specifies lagged Bitcoin prices, we used autoregressive terms for the estimation of the GARCH model which resulted in estimates closer to the ones reported in Dyhrberg (2016). *t*-statistics are in parentheses. *** (**, *) denotes significance at a 1% (5%, 10%) significance level.

Estimation Results

To implement the models, we tried different software packages (R, gretl, Gauss and STATA) but only managed to obtain results that are close but not equal to Dyhrberg (2016) with STATA. Moreover, the replication of the EGARCH-(1,1)-X model was only feasible using a two-step estimation procedure. First, the mean equation was estimated using the full set of explanatory variables as specified in Eq. (3). The residuals of this first-step estimation were then used to estimate the variance equation specified in Eq. (4).

The replication of the GARCH(1,1) model[3] is presented in Table 2. The coefficients are similar but not equal to the results presented in (Dyhrberg, 2016).

The replication results of the EGARCH(1,1) model are presented in Table 3. A comparison of the EGARCH coefficient estimates with the original model reveals that both the coefficient estimates and the signs of the coefficients are more similar than for the GARCH estimates. More specifically, all estimates in the EGARCH model have similar magnitudes and signs in both the original and the replication study except for the gold futures and gold spot ("cash") estimates.

Dyhrberg (2016) claims that "[...] bitcoin and gold have similarities when it comes to the volatility of the return [...]" (page 90). Since the two GARCH models are estimated for Bitcoin returns, the results cannot yield any information about the volatility of gold, or any other asset included as explanatory variable. A meaningful comparison is therefore impossible. All other interpretations are also potentially incorrect due to the use of non-stationary data. Furthermore, the results do not show that "Bitcoin may also be useful for hedging against the dollar" (Dyhrberg, 2016, p. 90). Since the levels of two highly correlated exchange rates are used, it is unlikely

[3] We assumed a Normal distribution for the ML-estimation. Using a Student-t distribution did not improve the results.

Table 3
Replication of EGARCH(1,1) with explanatory variables in mean and variance equation in Dyhrberg (2016).

Mean equation		
US Federal funds rate$_{t-1}$	0.132**	(2.72)
USD/EUR FX return$_{t-1}$	0.103***	(3.31)
USD/GBP FX return$_{t-1}$	− 0.0853	(− 1.87)
FTSE 100 index$_{t-1}$	0.0000122*	(2.48)
Gold futures$_{t-1}$	0.000287	(1.07)
Gold cash$_{t-1}$	− 0.000278	(− 1.03)
ΔLn(Bitcoin)$_{t-1}$	0.107***	(3.73)
Constant	− 0.1000	(− 1.46)
Variance equation		
US Federal funds rate$_{t-1}$	− 0.834***	(− 4.38)
USD/EUR FX return$_{t-1}$	1.368***	(9.98)
USD/GBP FX return$_{t-1}$	− 1.277***	(− 6.11)
FTSE 100 index$_{t-1}$	− 0.000110***	(− 5.14)
Gold futures$_{t-1}$	0.000249	(0.17)
Gold cash$_{t-1}$	− 0.000640	(− 0.44)
Constant	0.890**	(3.25)
α	0.0211	(1.39)
γ	0.494***	(22.50)
δ	0.877***	(126.89)
Observations	1767	

The table reports the estimation results of the best attempt to replicate the results in Table 3 of Dyhrberg (2016). Estimation was only feasible through a two-step estimation procedure. First, the mean equation was estimated with the full set of covariates in Eq. (3). In the second step, the residuals from the first-step estimation were used in the estimation of the variance equation specified in Equation (4). Even though Eq. (1) specifies lagged Bitcoin prices, we used "true" AR-terms for the estimation of the GARCH model. *t*-statistics are in parentheses. *** (**, *) denotes significance at a 1% (5%, 10%) significance level.

that such an effect can be identified from the present results.

3. Alternative analysis with an extended sample

In this section we propose an alternative analysis with a sample extended until July 14, 2017 to answer the main research question of Dyhrberg (2016), i.e. "if bitcoin behaves like a well-known financial asset or as something in between a commodity and a currency" (page 86). We also performed the analysis with the sample period used by Dyhrberg (2016) and find that the results do not change qualitatively.

We start with a descriptive analysis of Bitcoin returns, exchange rate returns, equity market index returns and gold returns. Note that we augmented the sample by including two trade-weighted currency indices (US dollar and the euro) as well as an additional global equity index (MSCI World).

3.1. Descriptive analysis

We construct the returns for all assets in our sample as percentage logarithmic price differences $r_t = 100 \times [\log(P_t) - \log(P_{t-1})]$. Table 4 presents descriptive statistics of the returns of all variables for the extended sample period with 1824 (2552) daily observations excluding (including) weekends (in the case of Bitcoin).

The descriptive statistics show that Bitcoin is in fact nowhere near gold, the US dollar (trade-weighted and with respect to major currencies) and financial assets such as the MSCI World equity index. The daily mean return is 0.4011% for Bitcoin and thus the

Table 4
Summary statistics.

	Mean	SD	Skew	Kurt	Min	Max	AR(1)	ADF	Obs
Bitcoin return	0.4011	5.8795	− 0.40	15.73	− 49.1528	42.4580	0.0263	− 23.02***	2552
US Federal Funds Rate	0.0005	0.0004	2.03	6.69	0.0001	0.0021	0.9988***	2.07	1824
USD/EUR FX return	− 0.0068	0.5896	0.02	4.44	− 2.2594	2.6000	− 0.0251	− 43.77***	1824
USD/GBP FX return	− 0.0083	0.5692	− 1.67	29.05	− 8.3120	2.7632	0.0150	− 41.99***	1824
USD FX index return	0.0082	0.3041	0.20	6.62	− 1.9891	1.7351	0.0232	− 14.29***	1824
EUR FX index return	− 0.0015	0.3796	− 0.24	6.36	− 2.9712	1.7981	− 0.0064	− 42.97***	1824
FTSE 100 return	0.0197	0.9509	− 0.20	5.46	− 4.7795	3.9429	0.0280	− 23.46***	1824
MSCI World return	0.0319	0.8334	− 0.55	7.76	− 5.2562	4.1122	0.1221***	− 21.37***	1824
Gold future return	0.0021	1.0611	− 0.79	10.14	− 9.8206	4.6176	− 0.0394*	− 44.39***	1824
Gold spot return	0.0022	1.0416	− 0.81	10.77	− 10.1624	5.4321	− 0.0177	− 11.70***	1824

*** (**, *) denotes significance at a 1% (5%, 10%) significance level.

Table 5
Contemporaneous return correlations.

	Bitcoin	USD/EUR	USD/GBP	USD FX Index	EUR FX Index	FTSE 100	MSCI World	Gold Cash	Gold Future
Daily returns									
Bitcoin	1								
USD/EUR	0.031	1							
USD/GBP	0.010	0.574***	1						
USD FX Index	0.003	− 0.734***	− 0.595***	1					
EUR FX Index	0.030	0.833***	0.153***	− 0.462***	1				
FTSE 100	0.020	0.154***	0.139***	− 0.369***	0.169***	1			
MSCI world	0.016	0.369***	0.388***	− 0.541***	0.273***	0.794***	1		
Gold cash	0.008	0.360***	0.227***	− 0.426***	0.182***	0.029	0.096***	1	
Gold future	0.005	0.315***	0.200***	− 0.397***	0.151***	0.019	0.088***	0.877***	1
Observations	1824								
Weekly returns									
Bitcoin	1								
USD/EUR	− 0.078	1							
USD/GBP	− 0.096*	0.522***	1						
USD FX index	0.046	− 0.712***	− 0.486***	1					
EUR FX index	− 0.042	0.851***	0.110**	− 0.483***	1				
FTSE 100	0.005	0.163***	0.058	− 0.392***	0.213***	1			
MSCI world	− 0.036	0.333***	0.294***	− 0.533***	0.275***	0.763***	1		
Gold cash	0.013	0.415***	0.242***	− 0.431***	0.259***	− 0.004	0.081	1	
Gold future	0.004	0.350***	0.197***	− 0.406***	0.220***	− 0.002	0.097*	0.867***	1
Observations	365								

Daily contemporaneous correlations do not include weekends since no trading occurs for the other assets during that period. Weekly returns are based on Wednesday-to-Wednesday (close) prices. *** (**, *) denotes significance at a 1% (5%, 10%) significance level.

largest average return. The MSCI World equity index yields the second highest mean return, namely 0.0319% which is more than ten times smaller than the average Bitcoin return. The standard deviation provides a similar picture and puts Bitcoin at the top with a standard deviation of 5.90% followed by gold futures returns (1.06%) and the FTSE 100 (0.95%). This is also illustrated by Fig. 2.

Table 5 presents the unconditional correlations of Bitcoin returns with all other returns for both daily (excluding weekends) and weekly (Wednesday-to-Wednesday) returns. It shows that Bitcoin returns are uncorrelated with all other asset returns, both on a daily as well as on a weekly frequency (except a small significant negative correlation with the USD/GBP exchange rate at weekly frequency). This provides opportunities for the risk management of portfolios as claimed by Dyhrberg (2016). The different signs observed between daily and weekly returns may be due to the different trading hours of Bitcoin versus equity for example. Specifically, in the case of daily data, the contemporaneous correlation estimates between Bitcoin and the other assets most likely do not exactly reflect the 'true' contemporaneous correlation since we do not take into account that the active trading hours across the different assets do generally not coincide with those of Bitcoin. It is remarkable that none of the correlation estimates between Bitcoin and any of the other entities is statistically significant except for the USD/GBP exchange rate. In contrast, all other correlation estimates are statistically significant with only some exceptions mainly for gold returns with equity index returns.

Hence, the correlation analysis suggests that Bitcoin is not related to gold, exchange rates, or stock markets. In contrast, gold and exchange rates exhibit a relatively strong relationship. Hence, as exchange rates are correlated with all other asset classes with the exception of Bitcoin, Bitcoin appears to be different from a traditional currency.

The analysis above illustrated that Bitcoin returns do not behave like "a well-known asset or as something in between a commodity and a currency [...]" (Dyhrberg, 2016, p. 86). The only similarity observed is that gold and stock markets are mostly uncorrelated as well, but that alone does not qualify Bitcoin as being similar to gold.

3.2. Comparing volatility processes across assets

This section discusses the estimation results of asymmetric GARCH models for all assets that are supposed to share certain features with Bitcoin. We propose to estimate univariate GARCH models for all assets separately which enables us to detect differences in the volatility processes across assets, in particular with respect to the asymmetric effect of positive and negative shocks, and volatility persistence. A focus on the volatility process of Bitcoin returns alone (with regressor variables as in Dyhrberg (2016) or without regressor variables) does not allow for a comparison with other assets' volatility if such processes are not estimated. Reference to other research may be misleading if this research used different models, sample periods, or control variables.[4]

We propose to estimate the asymmetric GARCH model of Glosten et al. (1993) (without exogenous variables in the variance equation) as follows:

$$r_t = c + \delta r_{t-1} + e_t, \tag{5}$$

[4] Estimating the models for each asset separately removes the necessity to aggregate the data to a common frequency. In the present case, this would either mean to drop the weekend observations of Bitcoin or to suitably interpolate weekend data for the assets that are not traded over the weekend or public holidays.

Table 6
GJR-GARCH(1,1).

	Bitcoin return	USD/EUR FX return	USD/GBP FX return	FTSE 100 return	MSCI World return	Gold future return	Gold spot return
Mean equation							
Constant	0.246***	− 0.0129	− 0.00276	− 0.00320	0.0253	0.00311	0.000655
	(3.98)	(− 1.04)	(− 0.24)	(− 0.18)	(1.63)	(0.13)	(0.03)
AR(1)	0.0721***	− 0.0244	− 0.00597	0.00646	0.0913***	− 0.0208	− 0.00558
	(3.17)	(− 1.01)	(− 0.23)	(0.26)	(3.98)	(− 0.71)	(− 0.19)
Variance equation							
α	0.222***	0.0331***	0.0727***	0.197***	0.193***	0.0472***	0.0572***
	(20.84)	(6.86)	(5.88)	(9.39)	(8.71)	(12.67)	(15.16)
γ	0.0801***	− 0.0234***	0.00387	− 0.222***	− 0.175***	− 0.0107*	− 0.00954
	(4.39)	(− 4.25)	(0.30)	(− 10.71)	(− 7.82)	(− 1.81)	(− 1.45)
β	0.759***	0.978***	0.918***	0.880***	0.864***	0.938***	0.922***
	(120.69)	(239.86)	(100.89)	(72.22)	(60.34)	(202.67)	(169.08)
Constant	0.883***	0.000298	0.00354***	0.0303***	0.0202***	0.0233***	0.0287***
	(30.21)	(1.23)	(3.00)	(9.05)	(6.47)	(6.25)	(6.16)
Observations	2551	1823	1823	1823	1823	1823	1823

t statistics in parentheses *** (**, *) denotes significance at a 1% (5%, 10%) significance level.

$$h_t = \omega + \alpha e_{t-1}^2 + \gamma I(e_{t-1} > 0) e_{t-1}^2 + \beta h_{t-1} \tag{6}$$

$$e_t \sim N(0, h_t), \tag{7}$$

where $I(\cdot)$ is the indicator function that takes on a value of 1 if $e_{t-1} > 0$ and 0 otherwise.[5]

Table 6 presents the results and demonstrates that Bitcoin returns exhibit very different volatility processes compared to the other assets: (i) The constant in the volatility equation is the highest, confirming that Bitcoin returns are the most volatile, (ii) the ARCH coefficient is the largest but close to that of the equity indices, (iii) the asymmetric GARCH term has a positive and statistically significant coefficient which is in stark contrast to all other assets' asymmetric effects. The positive coefficient implies that positive shocks increase the volatility by more than negative shocks whilst this asymmetry is the opposite for all other assets. (iv) the volatility persistence measured by the sum of the ARCH and GARCH terms implies that Bitcoin volatility is the most persistent amongst the considered assets: the estimates of the variance process are compatible with an integrated variance process as the sum $\alpha + \beta + \frac{1}{2}\gamma$ is greater than 1 (cp. Ling and McAleer, 2002). For all other models, the respective sum is smaller than one which makes Bitcoin stand out from all the considered assets.

Table 7 augments the estimated models with the US dollar trade-weighted index in the mean equation (5) to analyze the relationship with the US dollar as most assets are denominated in US dollar. The coefficient estimates show that Bitcoin is not related to contemporaneous changes of the US dollar whilst all other assets are strongly negatively related to the changes in the value of the currency (e.g. see Capie et al. (2005) for gold). More specifically, the coefficient estimate is 0.0307 for Bitcoin returns and between − 0.9 and − 1.6 for the other assets implying that the value of the US dollar is strongly and negatively related to all assets but Bitcoin. One explanation for this finding is that the high volatility of Bitcoin returns dominates any movements in the US dollar that might create a relationship between the two.

The estimates in the variance equation further show that the inclusion of the US dollar in the mean equation does not lead to major qualitative changes of the results. The change of the coefficient estimates for Bitcoin returns may also be related to the exclusion of weekends to synchronize the data with the regressor variable in the mean equation. This interpretation of the results is confirmed by a slightly different specification of the mean equation using lagged US dollar index returns. This model yields no significant coefficient estimates for the US dollar index across all assets and no changes in the GARCH estimates except a further strengthening of the asymmetric effect for Bitcoin.[6] These findings suggest that the asymmetric volatility effect of Bitcoin returns is stronger on weekdays than it is on weekends.

4. Summary and concluding remarks

The de-centralized mining of Bitcoin and the absence of any government backing the cryptocurrency is a reminder of essential features of gold while the idea that Bitcoin is a medium of exchange suggests that it resembles a currency. However, the empirical evidence presented in this article shows that Bitcoin is very different from gold and fiat currencies. This conclusion is in stark contrast to the findings of Dyhrberg (2016) and provide both a motivation and a justification for this study. Our econometric analysis shows that Bitcoin has unique risk-return characteristics, follows a different volatility process when compared with other assets and is uncorrelated with other assets. These empirical findings may be surprising given the design of Bitcoin as a Peer-to-Peer Electronic Cash System Nakamoto (2008). However, in its current stage, Bitcoin's excess returns and volatility rather resemble a highly

[5] Note that this specification of the Glosten et al. (1993)-GARCH model is specific to STATA. A negative and significant coefficient estimate for γ implies that positive shocks increase the variance by less than negative shocks.

[6] These estimation results can be obtained from the authors.

Table 7
GJR-GARCH(1,1)-X.

	Bitcoin return	USD/EUR FX return	USD/GBP FX return	FTSE 100 return	MSCI World return	Gold future return	Gold spot return
Mean equation							
Constant	0.368***	0.00417	0.0103	0.00422	0.0351**	0.0105	0.0101
	(4.38)	(0.50)	(1.11)	(0.24)	(2.57)	(0.52)	(0.51)
AR(1)	0.0860***	− 0.0336**	− 0.0254	0.00222	0.0620***	− 0.0452*	− 0.00699
	(3.38)	(− 2.14)	(− 1.33)	(0.10)	(3.32)	(− 1.91)	(− 0.28)
USD FX index return	0.0307	− 1.414***	− 1.028***	− 0.908***	− 1.225***	− 1.468***	− 1.577***
	(0.11)	(− 55.73)	(− 32.01)	(− 19.33)	(− 42.30)	(− 25.82)	(− 29.89)
Variance equation							
α	0.236***	0.0265***	0.0685***	0.225***	0.183***	0.0905***	0.104***
	(13.95)	(3.62)	(5.26)	(8.38)	(8.22)	(14.85)	(17.01)
γ	0.122***	0.0190**	0.0167	− 0.241***	− 0.198***	− 0.00755	− 0.00721
	(4.37)	(2.07)	(1.43)	(− 8.80)	(− 8.57)	(− 0.64)	(− 0.55)
β	0.727***	0.958***	0.913***	0.846***	0.864***	0.873***	0.854***
	(76.75)	(185.72)	(82.83)	(51.24)	(53.66)	(80.06)	(62.19)
Constant	1.313***	0.000921***	0.00284***	0.0401***	0.0221***	0.0406***	0.0414***
	(23.66)	(2.88)	(3.89)	(7.31)	(6.47)	(6.48)	(5.48)
Observations	1823	1823	1823	1823	1823	1823	1823

t statistics in parentheses *** (**, *) denotes significance at a 1% (5%, 10%) significance level.

speculative asset than gold or the US dollar.

It can be argued that it is easier to replicate and criticize existing work than to do novel research without a reference point. We acknowledge this and believe that Dyhrberg (2016) has helped to advance the research on Bitcoin by stimulating more research as evidenced by this replication study and by many other studies on Bitcoin.

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