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On the Intraday Behavior of Bitcoin: Open Review

Author: Giacomo De Nicola*†

Reviewers: Reviewer A, Reviewer B, Reviewer C, Reviewer D

Abstract. The final version of the paper "On the Intraday Behavior of Bitcoin" can be found in Ledger Vol. 6 (2021) 58-80, DOI 10.5915/LEDGER.2021.213. There were four reviewers involved in the review process, none of whom have requested to waive their anonymity at present, and are thus listed as Reviewers A through D. After initial review by Reviewers A and B, the submission was returned to the author with feedback for revision (1A). The author responded (1B) and resubmitted their work. The resubmission was sent to Reviewers A and B, whose decision was split, resulting in the editor seeking reviews from two other reviewers, here listed as C and D (2A). The author responded (2B) and resubmitted with further revisions. Upon the recommendation of a majority of reviewers, the submission was accepted, thus ending the peer review process. Author responses are bulleted for clarity.

1A. Review

Reviewer A

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

Yes

If you answered "yes" to the previous question, in one sentence, describe in your own words the novel contribution made by this paper:

It performs a complete analysis of the informational efficiency of Bitcoin.

Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Yes

* 1KjntxqWudCiprihdSpmhyUVhzhmx3BbuC
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Please assess the article's level of academic rigor.

Good (not excellent but a long way from poor)

Please assess the article's quality of presentation.

Good (not excellent but a long way from poor)

How does the quality of this paper compare to other papers in this field?

Top 50%

Please provide your free-form review for the author in this section.

The paper is nicely written and studies the intraday behavior of Bitcoin. However I have some comments:

1. In page 2 the author says: "With cryptocurrency being such a young financial phenomenon, literature on the subject is still relatively limited. Studies on market efficiency have started to emerge," I strongly disagree with the author. There are numerous studies on informational efficiency of BTC using many different techniques, and covering many different periods. You could do a simple search in Scopus, and you will find hundreds of papers dealing with this topic.

2. At the end of the literature the author says that there are a few of studies working with intraday data. This is true, but the author only cites one paper (Scaille et al, 2017). There are much more, and the author should acknowledge and compare his results with previous findings. Just to name a few of the most cited papers:

Sensoy, A. (2018). The inefficiency of Bitcoin revisited: A high-frequency analysis with alternative currencies. Finance Research Letters. https://doi.org/https://doi.org/10.1016/j.frl.2018.04.002

Hu, B., McInish, T., Miller, J., & Zeng, L. (2018). Intraday price behavior of cryptocurrencies. Finance Research Letters. https://doi.org/https://doi.org/10.1016/j.frl.2018.06.002

Dyhrberg, A. H., Foley, S., & Svec, J. (2018). How investible is Bitcoin? Analyzing the liquidity and transaction costs of Bitcoin markets. Economics Letters, 171, 140–143. https://doi.org/https://doi.org/10.1016/j.econlet.2018.07.032

Bariviera, A. F., Basgall, M. J., Hasperué, W., & Naiouf, M. (2017). Some stylized facts of the Bitcoin market. Physica A: Statistical Mechanics and Its Applications, 484, 82–90. https://doi.org/10.1016/j.physa.2017.04.159

3. Autocorrelations in Table 1, and Kurtosis in table 2, lacks of significance level.

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4. In page 10, when the author comments the seasonal decomposition (Holt-Winters), it should be interesting to explicitly put the model's formula.

5. Figure 9 and Table 2 are irrelevant. Instead of do such a large discussion on non-normality, I suggest to shorten de discussion, doing a normality test (for example, the famous Jarque-Bera test). This test uses jointly Kurtosis and Skewness. It is not necessary to explain what platykurtic or leptokurtic is, as it is basic descriptive statistics.

6. Figure 10 adds nothing, as it only show one significant lag. You should just to comment this finding in the text and delete the figure.

7. Exploiting the inefficiency (section 5.3) is very interesting. However, in order to evaluate the algorithmic approach as a measure of inefficiency, you should compare it with a "random strategy". For example, you could create a simple strategy by generating random numbers (between 0 and 1). Then you go long if random number is equal to or greater than 0.5, and go short otherwise. Then you can tell if your strategy outperforms a naïve random strategy.

8. As the author acknowledges, this paper is based on his masters thesis. I understand that you should go in deeper details in the thesis. However, I find the paper too long. I suggest to reduce some of the discussion of each empirical subsection. I think that the author could reduce by 1 page the text (in addition to deleting some tables/figures suggested previously).

Reviewer B

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

No

Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Important references are missing

Please assess the article's level of academic rigor.

Unsatisfactory (better than poor but a long way from excellent)

Please assess the article's quality of presentation.

Unsatisfactory (better than poor but a long way from excellent)

How does the quality of this paper compare to other papers in this field?

Bottom 50%

Please provide your free-form review for the author in this section.

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I do not think that this paper makes any significant contribution to the literature. Analysing the behaviour of Bitcoin using high-frequency data is of course a very interesting topic, but for that purpose proper econometric modelling should be done. There exists an extensive literature suggesting appropriate frameworks (for instance, GARCH models with Markov switching in the case of volatility) which is completely ignored by the author. This paper instead only carries out some descriptive analysis, which might be useful background information but for sure is not sufficient to gain a deep understanding of the properties of Bitcoin . In addition the paper is far too long: it does not read as a journal article but rather as a PhD chapter/thesis, which in fact it is - the author has not done the necessary editing and gives the game away on p.18 " Jumps and price reversals—The modeling of the Bitcoin financial series is not the subject matter of this thesis [SIC!]…". I am afraid this submission does not meet any of the requirements for publication in a respectable academic journal.

1B. Author Responses

Reviewer A

The paper is nicely written and studies the intraday behavior of Bitcoin.

- Many thanks for this assessment.

However I have some comments:

1. In page 2 the author says: "With cryptocurrency being such a young financial phenomenon, literature on the subject is still relatively limited. Studies on market efficiency have started to emerge," I strongly disagree with the author. There are numerous studies on informational efficiency of BTC using many different techniques, and covering many different periods. You could do a simple search in Scopus, and you will find hundreds of papers dealing with this topic.

- The reviewer is right: Some important literature was missing. I erased the phrase in question and added several additional references.

2. At the end of the literature the author says that there are a few of studies working with intraday data. This is true, but the author only cites one paper (Scaille et al, 2017). There are much more, and the author should acknowledge and compare his results with previous findings. Just to name a few of the most cited papers:

Sensoy, A. (2018). The inefficiency of Bitcoin revisited: A high-frequency analysis with alternative currencies. Finance Research Letters. https://doi.org/https://doi.org/10.1016/j.frl.2018.04.002

Hu, B., McInish, T., Miller, J., & Zeng, L. (2018). Intraday price behavior of cryptocurrencies. Finance Research Letters. https://doi.org/https://doi.org/10.1016/j.frl.2018.06.002

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Dyhrberg, A. H., Foley, S., & Svec, J. (2018). How investible is Bitcoin? Analyzing the liquidity and transaction costs of Bitcoin markets. Economics Letters, 171, 140–143. https://doi.org/https://doi.org/10.1016/j.econlet.2018.07.032

Bariviera, A. F., Basgall, M. J., Hasperué, W., & Naiouf, M. (2017). Some stylized facts of the Bitcoin market. Physica A: Statistical Mechanics and Its Applications, 484, 82–90. https://doi.org/10.1016/j.physa.2017.04.159

- Again, the reviewer is right. I added all suggested references and some more.

3. Autocorrelations in Table 1, and Kurtosis in table 2, lacks of significance level.

- Table 2 was removed as suggested by the referee in a later comment. In Table 1, all values are highly significant, as was already stated in the main body of the manuscript, in which I also specified that the highest p-value is lower than 10^{-9} . The statistical significance of all values is now also included in the caption of the table for additional clarity.

4. In page 10, when the author comments the seasonal decomposition (Holt-Winters), it should be interesting to explicitly put the model's formula.

- I added the model formula as well as a more accurate reference.

5. Figure 9 and Table 2 are irrelevant. Instead of do such a large discussion on non-normality, I suggest to shorten de discussion, doing a normality test (for example, the famous Jarque-Bera test). This test uses jointly Kurtosis and Skewness. It is not necessary to explain what platykurtic or leptokurtic is, as it is basic descriptive statistics.

- Figure 9 and Table 2 were cut as suggested, together with the lengthy discussion on Kurtosis. I also performed and added the Jarque-Bera normality test.

6. Figure 10 adds nothing, as it only show one significant lag. You should just to comment this finding in the text and delete the figure.

- Figure 10 was removed, leaving the explanation of the finding in the body of the paper.

7. Exploiting the inefficiency (section 5.3) is very interesting. However, in order to evaluate the algorithmic approach as a measure of inefficiency, you should compare it with a "random strategy". For example, you could create a simple strategy by generating random numbers (between 0 and 1). Then you go long if random number is equal to or greater than 0.5, and go short otherwise. Then you can tell if your strategy outperforms a naïve random strategy.

- I found this a very good idea, and added it to the paper. In particular, I implemented the purely random strategy proposed by the reviewer and repeated it 10.000 times. The details and results of this analysis can be found at the bottom of page 18 of the revised manuscript.

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8. As the author acknowledges, this paper is based on his masters thesis. I understand that you should go in deeper details in the thesis. However, I find the paper too long. I suggest to reduce some of the discussion of each empirical subsection. I think that the author could reduce by 1 page the text (in addition to deleting some tables/figures suggested previously).

- Again, the referee makes a very good point here. On the one hand, the overview-like nature of the paper keeps it from being too short; on the other hand, the presentation could definitely be improved. In addition to implementing all suggested deletions of non-essential plots and tables, I also cut the two plots related to the analysis of intra-hour 5-minutes volatility, which were a bit redundant: I now simply mention how the results for intra-hour volatility are similar to the intraday hourly ones. Moreover, I worked extensively on making the presentation more efficient all across the paper, and especially so in the empirical sections, as suggested by the referee. With all of this, and after adding relevant references, the length of the manuscript was reduced by 4 pages, bringing the total length of the paper from 26 to 22 pages.

Reviewer B

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

No

Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Important references are missing

Please assess the article's level of academic rigor.

Unsatisfactory (better than poor but a long way from excellent)

Please assess the article's quality of presentation.

Unsatisfactory (better than poor but a long way from excellent)

How does the quality of this paper compare to other papers in this field?

Bottom 50%

Please provide your free-form review for the author in this section.

I do not think that this paper makes any significant contribution to the literature. Analysing the behaviour of Bitcoin using high-frequency data is of course a very interesting topic, but for that purpose proper econometric modelling should be done. There exists an extensive literature suggesting appropriate frameworks (for instance, GARCH models with Markov switching in the case of volatility) which is completely ignored by the author. This paper instead only carries out some descriptive analysis, which might be useful background

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information but for sure is not sufficient to gain a deep understanding of the properties of Bitcoin.

- I am sorry the reviewer did not find the paper to be of interest. An important point which deserves clarification is that the paper does not aim at performing econometric modeling of the bitcoin series, but is instead focused on performing an in-depth descriptive analysis of the intraday price behavior of the cryptocurrency, and on comparing it to traditional financial assets. This has now been stated clearly at page 3 of the manuscript. Even though in this context econometric modelling would certainly be fitting and adequate, I believe this type of analysis to be interesting in its own right, since it sheds light on several similarities as well as on some important differences between Bitcoin and other assets. Nonetheless, the reviewer is right in that important references to the MS-GARCH literature were missing. Some of them have been included in the revised manuscript.

In addition the paper is far too long: it does not read as a journal article but rather as a PhD chapter/thesis, which in fact it is - the author has not done the necessary editing and gives the game away on p.18 " Jumps and price reversals—The modeling of the Bitcoin financial series is not the subject matter of this thesis [SIC!]…". I am afraid this submission does not meet any of the requirements for publication in a respectable academic journal.

- I agree with the reviewer in that the paper was too long. As stated in the response to Reviewer A, on the one hand, the overview-like nature of the paper keeps it from being too short; on the other hand, the presentation could definitely be improved. I also thank the reviewer for pointing out the mistake at page 18, I corrected that. I would also like to point out that the fact that the paper originates from the work done in my masters thesis is openly stated in the acknowledgements section: I would therefore say there was no game to give away. I have now restructured and shortened the paper to make the presentation more efficient: The style of the manuscript is now more concise and, hopefully, in line with that of a journal article. The total length of the paper was cut from 26 down to 22 pages, with all modifications being visible in the change-tracking version submitted together with the revised manuscript.

2A. Second Round Review

Reviewer A

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

Yes

If you answered "yes" to the previous question, in one sentence, describe in your own words the novel contribution made by this paper

It provides an empirical analysis of high frequency Bitcoin time series.

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Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Yes

Please assess the article's level of academic rigor.

Good (not excellent but a long way from poor)

Please assess the article's quality of presentation.

Good (not excellent but a long way from poor)

How does the quality of this paper compare to other papers in this field?

Top 50%

Please provide your free-form review for the author in this section.

The revised version of the paper is better than the original one. I have only one correction remaining. In table 1, instead of saying "all coefficients are highly significant", you should say "coefficients are significant at 1% level" (or the corresponding significance level).

Reviewer B

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

No

Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Important references are missing

Please assess the article's level of academic rigor.

Unsatisfactory (better than poor but a long way from excellent)

Please assess the article's quality of presentation.

Unsatisfactory (better than poor but a long way from excellent)

How does the quality of this paper compare to other papers in this field?

Bottom 50%

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Please provide your free-form review for the author in this section.

I have had a look at the revised version of this paper. It has been slightly improved by shortening it a bit and stating more precisely a few points previously relatively obscure. However, my overall assessment does not change: this is a fairly long, exclusively descriptive paper without any rigorous theory to develop hypothesis to test and without any empirical modelling, in my book this might be sufficient for a dissertation, not for a journal article.

Reviewer C

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

Yes

If you answered "yes" to the previous question, in one sentence, describe in your own words the novel contribution made by this paper:

Section 5.3 is new as it presents a trading experiment.

Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Important references are missing

Please assess the article's level of academic rigor.

Good (not excellent but a long way from poor)

Please assess the article's quality of presentation.

Good (not excellent but a long way from poor)

How does the quality of this paper compare to other papers in this field?

Top 50%

Please provide your free-form review for the author in this section.

The paper is well written; however, it does not follow the typical research paper format as it is rather more descriptive than an empirical investigation. There are few comments/suggestions to the author.

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Abstract
The author should be clearer as to which markets the Bitcoin is going to be compared, considering “financial markets” it’s too big concept. Also, what are the “standard patterns” must be clearer. If the market is inefficient, one would not expect to see mean-reversion.

Introduction
There is no clear indication as to why it is imperative to investigate the issue at hand. The author states that the “scope of the article is to provide an overview of the intraday behaviour of the Bitcoin price, analysing it in terms of informational efficiency”, however this has been done in the past and one naturally asks: why it is important to further analyse this market and what can we learn from it? Moreover, aims and objectives are not discussed. Neither there is a theoretical foundation presented that supports the investigation at hand.

Literature Overview
This section is purely descriptive, and it would hugely benefit from making it critical so as to be able to find a research gap and formulate the research questions, which are missing.

Data
This section discusses the time series of Bitcoin; however, it is not clear in what currency the data was acquired; is the price of the Bitcoin in US dollars? Later however on few of the figures one can conjure that the price of Bitcoin is in US dollars.

Traditional Financial Markets and Bitcoin
It is not clear exactly which financial assets the Bitcoin is being compared to. There is reference to stock markets and exchange markets on page 11, and such it seems the author benchmarks the Bitcoin market to a hypothetical ‘financial market’ – ideally one would contrast the Bitcoin market to either stock markets, money markets, bond markets, commodity markets or foreign exchange markets. References are missing from this section with few exceptions. Stylised facts and summary statistics are described at length. It seems that the author looks at the financial market in general and that causes problems considering there are a variety of assets the Bitcoin can be compared to and conclusions drawn. The Legend for Figure 1 denotes the blue line as Bitcoin and the red one as Euro. However, within the text on page four the two time series seem to be the Bitcoin/Dollar and the Euro/Dollar series, and such there is no consistency on notation of the currencies. On page 5 the author notes that the “Bitcoin is by far the least volatile asset in the cryptocurrency class”, yet this claim is not referenced. The author goes on to provide a volatility figure (Figure 2) explaining that there are high volatility clusters, which contradicts the earlier statement that Bitcoin in fact is not that volatile. It is still not clear whether Figure 2 plots the US dollar price of Bitcoin, considering the literature in general looks at an ‘exchange rate’ when discussing the price of Bitcoin. On page 7 the author claims that “traditional markets open and close at certain times”, however this were only true if one would not consider the over-the-counter markets that sell financial instruments 24/7; in this particular case the OTC markets are the exchanges through which one can exchange bitcoins to dollars and vice versa at any given time. Also, on page 7 the author uses the Pearson correlation test for the volume and intraday volatility, however Pearson autocorrelation works only with normally distributed data and such one should use

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either the Spearman correlation or Kendall's tau. On page 8 the author concludes by looking at Figure 5 results that "Bitcoin trading is performed at least to some extent by trading firms", which is in sharp contrast with the information provided on the bottom of page 1 claims that "many professional and institutional players chose to stay away from investing in the digital currency" – yet it is not clear who are the trading firms and professional players. On the lines of non-linear distribution aspect of the data, at the bottom of page 9 the author notes that the Bitcoin data is non-normally distributed, which is true, and such to be statistically correct, one would not implement linear autocorrelation test (results presented in Table 1 and later), but rather resort to using non-linear correlation tests that better describe non-linear data (as explained earlier) This is also true for the corelation test performed between volatility and returns. The distribution of returns' results would have benefitted to be displayed via a figure. On page 12 the author briefly mentions market efficiency, however stylised facts should always be discussed in light of relevant finance theory. Section 5.2 is very well executed. On page 16 section 5.3 is titled "Exploiting the inefficiency ...", however it is not clear whether the author refers to Bitcoin's inefficiency or to something else? Otherwise, this section is very well executed. Conclusions section is very well executed; however, it would have benefitted from a short discussion on relevant theories in light of results and also contrasted to findings in the literature. Also, one paragraph should be included on the implications for industry, in particular for traders.

Reviewer D

Does this paper represent a novel contribution to cryptocurrency or blockchain scholarship?

Not sure

Is the research framed within its scholarly context and does the paper cite appropriate prior works?

Important references are missing

Please assess the article's level of academic rigor.

Good (not excellent but a long way from poor)

Please assess the article's quality of presentation.

Unsatisfactory (better than poor but a long way from excellent)

How does the quality of this paper compare to other papers in this field?

Top 50%

Please provide your free-form review for the author in this section.

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General comment:
The central issue the paper has are the links between the literature, motivation, research question, analytical approach and contribution. The introduction should clearly state what the motivation is to study this area, bringing in what previous literature has investigated, why it is important and what this paper brings to the discussion. To that end the introduction should also state what analytical approach is used and how it is used to answer the research question. The introduction should then go over the high-level results and relate them back to the literature and discuss broader implications. In the current version of the paper this is not done. As a result, it is unclear what the contribution of the paper is.

Specific comments:
"Moreover, we find that the tendency for price to mean-revert increases, in percentage terms, together with the size of the price movement that precedes the reversal." From abstract. I'm not entirely sure what the author means.
From the abstract, it is unclear what the research question is and what your contribution is. This should be much clearer.

From the first paragraph in the introduction, it seems that the author's motivation is "the traders of cryptocurrencies are non-professional and irrational which is why it is interesting to analyse bitcoin from a behavioural finance perspective." If that is the case you need (1) references to support your statements about the characteristics of the traders, (2) be very clear about the time series you are using as the trader composition changes over time, (3) be more specific about what behavioural aspect you are studying (it's a big field), (4) be specific about how you will answer your research question and (5) how does this paper contribute to the literature. To that end I don't think you need the long background story about what a cryptocurrency is. Only keep the background which is necessary for your argument. If my assumption about the motivation is wrong, then the author needs to be a lot clearer.

In addition, how does comparing bitcoin to traditional markets tell us something about the informational efficiency?

The author states "We exploit previous literature on high-frequency finance and show that phenomena that are usually limited to very small timeframes and mostly attributable to orderbook-related effects manifest themselves at larger timeframes and more prominently in the Bitcoin market, in a way that is not solely imputable to market microstructure and can be considered evidence for market inefficiency." (1) Be specific about what phenomena you are talking about, (2) relate it back to the literature, (3) relate it back to your research question, and (4) what does this tell us in general (ask yourself, so what?). The author answers some of these comments in the sentence after, but then drop the build-up. Talk about the high level results and what they mean.

Based on the comments above, I'd suggest that the author integrates the literature review into the introduction. The author needs the literature to show what we already know and what we don't know and how the author contributes. A good approach is to either find a gap in the literature or a disagreement in the literature to motivate the paper.

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"There is a large body of literature documenting intraday patterns such as intraday variations in returns, volatility, volume and bid-ask spreads in financial time series." References needed.

The dataset is from March 1st, 2015 to June 27th, 2018. How does the author take into account the development of the market over the time period?

"All of the data cleaning, analysis and visualization were conducted using R" The author does not need to state this.

The paper is very long and has a lot of "filler sentences". The author could cut out a lot of "filler", by going straight to the point and not repeating statements.

It is difficult to talk about the intraday variations when figure 2 is a timeseries over four years. Consider averaging across to show the actual intraday variation.
Form the trading volume it would be useful to separate the analysis into pre/post 2017 as we cannot compare the market and liquidity in 2015 with that of 2018.

Always write in present tense, active voice

2B. Authors' Response to Second Round Review

Reviewer C

The paper is well written;

- Thank you for this assessment.

however, it does not follow the typical research paper format as it is rather more descriptive than an empirical investigation. There are few comments/suggestions to the author.

- I have reworked the paper extensively, with specific focus on the points raised by the anonymous referee. Many thanks for the constructive criticism, which I believe contributed to improve the manuscript substantially.

Abstract
The author should be clearer as to which markets the Bitcoin is going to be compared, considering "financial markets" it's too big concept.

- I now specify that the comparison is with ″traditional financial markets, such as those of stocks and exchange rates″.

Also, what are the "standard patterns" must be clearer. If the market is inefficient, one would not expect to see mean-reversion.

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- As specified in the abstract, the main standard pattern from which we deviate is the absence of negative autocorrelation in medium-frequency returns, such as those computed at one, two and four hours timeframes. While some mean-reversion is to be expected at very high frequencies due to effects related to market microstructure, autocorrelation at those longer timeframes is not standard (see e.g. Cont, 2001, Bianco et al., 2006 and Sewell, 2011, all referenced in the manuscript). I now tried to make this more precise in the manuscript.

Introduction
There is no clear indication as to why it is imperative to investigate the issue at hand. The author states that the "scope of the article is to provide an overview of the intraday behaviour of the Bitcoin price, analysing it in terms of informational efficiency", however this has been done in the past and one naturally asks: why it is important to further analyse this market and what can we learn from it? Moreover, aims and objectives are not discussed. Neither there is a theoretical foundation presented that supports the investigation at hand.

- The reviewer makes a very good point, in that the motivation and scope of the article needed to be made more clear. The introduction has been reworked extensively, with specific focus on this point. In short, we now argue that, despite previous studies studying the matter, a comprehensive understanding of intraday price and efficiency dynamics of cryptocurrencies is still lacking, and the general scope of this article is therefore to provide an overview of the intraday behavior of Bitcoin price in the period from 2015 to 2018 to further shed light on the matter. More specifically, the paper contributes to the growing body of literature in two main ways. Firstly, given that the one at hand is still a relatively young market, it is important to understand whether or not recent behavior aligns with previous findings. I therefore analyze the series of Bitcoin price at the intraday level in the considered period, specifically focusing on outlining stylized facts, and highlighting similarities and differences with traditional markets. The second way in which this paper contributes is by focusing on the most striking of those differences, namely is the unusual presence of highly significant first-order negative autocorrelation of intraday medium-frequency returns. This phenomenon is, to the best of my knowledge, not previously documented for the Bitcoin market. I then dig deeper into this finding and go on to show, by means of a very simple trading strategy, the potential exploitability of this systematic intraday mean-regressing behavior. The contributions are now described more precisely in the introduction; this hopefully renders the scope of the paper far clearer.

Literature Overview
This section is purely descriptive, and it would hugely benefit from making it critical so as to be able to find a research gap and formulate the research questions, which are missing.

- The section has now been removed and incorporated in the introduction, to better highlight the gaps that motivate this paper, and to phrase the research questions more directly. The way this has been done is already discussed in the response to the

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previous point.

Data

This section discusses the time series of Bitcoin; however, it is not clear in what currency the data was acquired; is the price of the Bitcoin in US dollars? Later however on few of the figures one can conjure that the price of Bitcoin is in US dollars.

- We now specify that prices are denominated in US dollars.

Traditional Financial Markets and Bitcoin

It is not clear exactly which financial assets the Bitcoin is being compared to. There is reference to stock markets and exchange markets on page 11, and such it seems the author benchmarks the Bitcoin market to a hypothetical 'financial market' – ideally one would contrast the Bitcoin market to either stock markets, money markets, bond markets, commodity markets or foreign exchange markets. References are missing from this section with few exceptions. Stylised facts and summary statistics are described at length. It seems that the author looks at the financial market in general and that causes problems considering there are a variety of assets the Bitcoin can be compared to and conclusions drawn.

- I now specify that the comparison is with "traditional financial assets such as stocks and exchange rates". Even though different types of markets naturally have different characteristics, the comparison here is phrased generally on purpose. This is because the price behavior of completely different financial assets does share some quite nontrivial statistical properties. Such properties, common across a wide range of instruments, markets and time periods are the so-called stylized empirical facts (and I here refer to the cited paper by Cont, 2001, "Empirical properties of asset returns: stylized facts and statistical issues"). Nonetheless, the reviewer is right in that more references are beneficial and necessary in this regard: I added several.

The Legend for Figure 1 denotes the blue line as Bitcoin and the red one as Euro. However, within the text on page four the two time series seem to be the Bitcoin/Dollar and the Euro/Dollar series, and such there is no consistency on notation of the currencies.

- I now changed the legend to make clear that those depicted are indeed rates of exchange with the US dollar.

On page 5 the author notes that the "Bitcoin is by far the least volatile asset in the cryptocurrency class", yet this claim is not referenced.

- I now added a pertinent reference (Bouri et. al, 2021) and removed the "by far".

The author goes on to provide a volatility figure (Figure 2) explaining that there are high volatility clusters, which contradicts the earlier statement that Bitcoin in fact is not that volatile.

- The earlier phrase: "Another thing to note is that, while it may seem hard to believe, Bitcoin is by far the least volatile asset in the cryptocurrency class" is saying that

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> Bitcoin is the least volatile among cryptocurrencies, and not little volatile in general. This goes to show my point that, while Bitcoin is the least volatile among crypto-assets, it is still incredibly volatile, which underlines how volatile crypto assets are in general.

It is still not clear whether Figure 2 plots the US dollar price of Bitcoin, considering the literature in general looks at an 'exchange rate' when discussing the price of Bitcoin.

- Figure 2 plots the volatility of the price of Bitcoin denominated in US dollars. This is now specified in the caption. I similarly specified this in the caption for Figure 8.

On page 7 the author claims that "traditional markets open and close at certain times", however this were only true if one would not consider the over-the-counter markets that sell financial instruments 24/7; in this particular case the OTC markets are the exchanges through which one can exchange bitcoins to dollars and vice versa at any given time.

- The referee makes a good point, in that some markets for traditional assets are open 24/7. The statement has been weakened to "many traditional markets open and close at certain times". In the case of cryptocurrency exchanges, both centralized exchanges (like Bitstamp) and decentralized exchanges offer 24/7 trading.

Also, on page 7 the author uses the Pearson correlation test for the volume and intraday volatility, however Pearson autocorrelation works only with normally distributed data and such one should use either the Spearman correlation or Kendall's tau.

- The referee here raises an interesting point regarding the use of Pearson's r as opposed to other measures of non-linear correlation. The linear correlation coefficient is informative about the degree of linear association between the two random quantities regardless of whether their joint distribution is normal. In fact, If we violate the bivariate normality assumption then the sample correlation coefficient remains approximately unbiased, but may not be efficient (and thus alternative measures may have more attractive small-sample properties). However, the bivariate normality is not a necessary requirement for the effective use of the r statistic (see e.g. "Effective use of Pearson's product-moment correlation coefficient" by Ruth et al. for more details). Given that the use of Pearson's r is the standard in the finance literature (see e.g. all of the previously cited paper on stylized facts which consider linear correlation), and given that the goal is here to have a parametric measure of the linear association between different time series, I believe that there is value in using linear correlation over Spearman's rho or Kendall's tau in this context.

On page 8 the author concludes by looking at Figure 5 results that "Bitcoin trading is performed at least to some extent by trading firms", which is in sharp contrast with the information provided on the bottom of page 1 claims that "many professional and institutional players chose to stay away from investing in the digital currency" – yet it is not clear who are the trading firms and professional players.

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- The statement “many professional and institutional players chose to stay away from investing in the digital currency” has been cut from the introduction. I now talk about how the Bitcoin market is composed of both institutional and retail traders, consistently with the findings of Baur et al. (2019) and Scharnowski (2021).

On the lines of non-linear distribution aspect of the data, at the bottom of page 9 the author notes that the Bitcoin data is non-normally distributed, which is true, and such to be statistically correct, one would not implement linear autocorrelation test (results presented in Table 1 and later), but rather resort to using non-linear correlation tests that better describe non-linear data (as explained earlier) This is also true for the corelation test performed between volatility and returns.

- The choice of using Pearson’s r over other measures of association has already been discussed in the answer to the previous point.

The distribution of returns’ results would have benefitted to be displayed via a figure.

- As suggested by the referee, I now added Figure 7 (on page 10), which depicts the kernel density of Bitcoin returns computed at the two hours timeframe and compares it with a normal distribution with the same mean and variance. The plot highlights the positive Kurtosis of the distribution of Bitcoin returns.

On page 12 the author briefly mentions market efficiency, however stylised facts should always be discussed in light of relevant finance theory.

- Good point, I now included pertinent references supporting the statements on market efficiency.

Section 5.2 is very well executed.

- Thank you for this.

On page 16 section 5.3 is titled “Exploiting the inefficiency ...”, however it is not clear whether the author refers to Bitcoin’s inefficiency or to something else?

- This indeed refers to Bitcoin’s inefficiency. I now specify this in the section’s title.

Otherwise, this section is very well executed.

- Thank you for this.

Conclusions section is very well executed; however, it would have benefitted from a short discussion on relevant theories in light of results and also contrasted to findings in the literature. Also, one paragraph should be included on the implications for industry, in particular for traders.

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- Thank you for the pertinent suggestions. I now included in the concluding section both a paragraph on the implications for the industry and some more words on how our findings relate to the existing literature.

Reviewer D

- Before addressing the specific points one by one, I would like to thank the reviewer for their constructive criticism, which I believe massively helped in improving the paper significantly through both major and minor changes.

The central issue the paper has are the links between the literature, motivation, research question, analytical approach and contribution. The introduction should clearly state what the motivation is to study this area, bringing in what previous literature has investigated, why it is important and what this paper brings to the discussion. To that end the introduction should also state what analytical approach is used and how it is used to answer the research question. The introduction should then go over the high-level results and relate them back to the literature and discuss broader implications. In the current version of the paper this is not done. As a result, it is unclear what the contribution of the paper is.

- The referee makes a good point in that the paper should be more clear about its aims and contributions from the beginning. I now incorporated the literature overview section into the introduction to move in this direction. I additionally extensively revamped the introduction,
- giving it a structure that be outlined as follows:
    - General short introduction on Bitcoin and the crypto markets
    - Why it is especially interesting to study the price of Bitcoin
    - Brief summary of the existing literature on the subject
    - Motivation and scope of the paper
    - More specific contributions of the paper and general implications
    - Outline of the rest of the article
- I believe (and hope) the new introduction makes the paper's motivation, aims and contributions much clearer.

Specific comments:
"Moreover, we find that the tendency for price to mean-revert increases, in percentage terms, together with the size of the price movement that precedes the reversal." From abstract. I'm not entirely sure what the author means.

- This is now stated more clearly in the abstract ("It is also found that larger price movements lead to stronger reversals, in percentage terms").

From the abstract, it is unclear what the research question is and what your contribution is. This should be much clearer.

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- The abstract underwent some modifications. It is now hopefully clearer what the scope of the paper and implied research question (the comparison of Bitcoin with other markets like those of stocks and exchange rates at the intraday level) as well as contributions (shedding light on similarities and differences, pointing out and digging deeper into the presence of negative autocorrelation, showing the potential exploitability of the phenomenon) are.

From the first paragraph in the introduction, it seems that the author's motivation is "the traders of cryptocurrencies are non-professional and irrational which is why it is interesting to analyse bitcoin from a behavioural finance perspective." If that is the case you need (1) references to support your statements about the characteristics of the traders, (2) be very clear about the time series you are using as the trader composition changes over time, (3) be more specific about what behavioural aspect you are studying (it's a big field), (4) be specific about how you will answer your research question and (5) how does this paper contribute to the literature. To that end I don't think you need the long background story about what a cryptocurrency is. Only keep the background which is necessary for your argument. If my assumption about the motivation is wrong, then the author needs to be a lot clearer.

- I agree with the referee, in that this part of the introduction would benefit from some changes. Among other changes, the mentioned statement has been weakened and rendered more precise. Responding point by point:

- (1) and (2): We now refer to the mixed composition of market participants, which I believe is likely to have changed over time (with references).

- (3): I specify that we are studying price behavior and predictability.

- (4) and (5): The implied research questions are hopefully more clear (see previous response).

- The introduction has also generally been made lighter by removing some of the background and fused with the literature review section.

In addition, how does comparing bitcoin to traditional markets tell us something about the informational efficiency?

- I agree about this point: I am here talking about efficiency in broader terms, referring to price behavior in general. The term "informational efficiency" has now been removed.

The author states "We exploit previous literature on high-frequency finance and show that phenomena that are usually limited to very small timeframes and mostly attributable to orderbook-related effects manifest themselves at larger timeframes and more prominently in the Bitcoin market, in a way that is not solely imputable to market microstructure and can be considered evidence for market inefficiency." (1) Be specific about what phenomena you are talking about, (2) relate it back to the literature, (3) relate it back to your research question,

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and (4) what does this tell us in general (ask yourself, so what?). The author answers some of these comments in the sentence after, but then drop the build-up. Talk about the high level results and what they mean.

- In the comprehensive reworking of the introduction, the mentioned statement has been deleted. In its place there is now a more accurate and orderly explanation of the scope of the paper and its contributions, which can be found on page 2. The build up has now been dropped, and the structure is now more direct and, hopefully, clear.

Based on the comments above, I'd suggest that the author integrates the literature review into the introduction. The author needs the literature to show what we already know and what we don't know and how the author contributes. A good approach is to either find a gap in the literature or a disagreement in the literature to motivate the paper.

- The introduction is now fused with literature review, as previously stated. The more linear structure of the introduction should now make clear that the gap lies in the lack of a general consensus on intraday behavior of bitcoin price and in the non-documentation of the systematic mean reversion at the medium-frequency level. It should now be clear that that is how this paper contributes to the pre-existing literature.

"There is a large body of literature documenting intraday patterns such as intraday variations in returns, volatility, volume and bid-ask spreads in financial time series." References needed.

- This phrase is now not anymore present, but the concept is still expressed. Referenced here are Cont (2001), Sewell (2011), Campbell (1997), and Pagan (1996).

The dataset is from March 1st, 2015 to June 27th, 2018. How does the author take into account the development of the market over the time period?

- The reviewer is right, we do not take the development of the market into account, as I think this is beyond the scope of this paper. It would certainly be interesting and useful to go in this direction. This point is now mentioned as one of the limitations of this study, and as a potential direction for further research, in the concluding section.

"All of the data cleaning, analysis and visualization were conducted using R" The author does not need to state this.

- This statement was deleted.

The paper is very long and has a lot of "filler sentences". The author could cut out a lot of "filler", by going straight to the point and not repeating statements.

- I have tried to go in this direction, and I removed several phrases that were redundant. This resulted in a cut of approximately one page of text. Note that the overall length of

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the manuscript did not decrease, as I also made several additions that were suggested by the referees, including an extra figure.

It is difficult to talk about the intraday variations when figure 2 is a timeseries over four years. Consider averaging across to show the actual intraday variation.

- I added a rolling 30-days average to the plot in Figure 2. This should make the patterns clearer.

Form the trading volume it would be useful to separate the analysis into pre/post 2017 as we cannot compare the market and liquidity in 2015 with that of 2018.

- I agree that this would be interesting. In fact, the master thesis that inspired this article included an entire section dedicated to the analysis of 2018 only. Unfortunately the paper is already quite long, and was far too long with that included, so I had to cut it, among other things. I added the potential for splitting the analysis in pre/post 2017 to the discussion in the concluding section, as a further research direction.

Always write in present tense, active voice

- Thank you for this suggestion. I have modified the paper keeping this in mind, and changed many instances of active voice into passive.

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