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A theory of information overload applied to perfectly efficient financial markets

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Abstract

Purpose – In the era of big data investors deal every day with a huge flow of information. Given a model populated by economic agents with limited computational capacity, the paper shows how "too much" information could cause financial markets to depart from the assumption of informational efficiency. The purpose of the paper is to show that as information increases, at some point the efficient market hypothesis ceases to be true. In general, the hypothesis cannot be maintained if the use of the maximum amount of information is not optimal for investors.

Design/methodology/approach – The authors use a model of cognitive heterogeneity to show the inadequacy of the notion of market efficiency in the modern society of big data.

Findings – Theorem 1 proves that as information grows, agents' processing capacities do not, so at some point there will be an amount of information that no one can fully use. The introduction of computer-based processing techniques can restore efficiency, however, also machines are bounded. This means that as the amount of information increases, even in the presence of non-human techniques, at some point it will no longer be possible to process further information.

Practical implications – This paper explains why investors very often prefer heuristics to complex strategies.

Originality/value – This is, to the authors' knowledge, the first model that uses information overload to prove informational inefficiency. This paper links big data to informational efficiency, whereas Theorem 1 proves that the old notion of efficiency is not well-founded because it relies on unlimited processing capacities of economic agents.

Keywords Behavioural finance, Big data, Information economics, Informational efficiency, Information overload

Paper type Research paper

1. Introduction

The traditional finance theory assumes that individuals use all the relevant information to form their investment decisions and, consequently, prices describe the relevant features of each security. In this paper, we assess the following question: do economic agents always use all the relevant information in their decisional process? Before the massive spread of computer technology, obtaining information was difficult. Many investors had to rely on the work of professionals, who were in many cases untrained individuals. In this extremely uncertain scenario, information was a precious good and its cost was not negligible. With the advent of the "Internet era", the quantity of available information grew exponentially. For example, search engines now produce millions of related contents just by searching on a few words. Therefore, we do not face anymore a problem of scarce and costly information, but we must deal with massive amounts of data.

JEL Classification — D4, D9, G1, G4

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Besides the role of data and information, also the nature of economic agents was reconsidered. The studies of several authors, such as Simon (Simon, 1955, 1956) or Kahneman and Tversky (Kahneman and Tversky, 1979; Tversky and Kahneman, 1986), posed serious doubts over the reliability of the rationality assumption in economic models and, coherently with many studies on the human brain, favoured the hypothesis of a "bounded" rationality. We are firmly convinced that reproducing the cognitive limits of individuals into economic models, although difficult, yields better results.

The novelty of this work consists in showing how information overload combined with big data affects the decision-making process at the individual level and how this can produce informational inefficiency in financial markets. The result is that even an ideal financial market (without costs of trading and noise, where information is freely available and "good") may produce inefficiencies given that agents are limited in their processing routines. The main result of the paper (Theorem 1) proves that as information grows, agents' processing capacities do not, so at some point there will be an amount of information that no one can fully use. The result is obtained by means of a simple mathematical model of rational expectations introducing an information processing cost function to reproduce information overload. The introduction of computer-based processing techniques can reduce this cost and restore informational efficiency, however, machines also have a limited capacity to store and elaborate information (see, for example, the Bekenstein bound). This means that as the amount of information increases, even in the presence of non-human techniques (such as machine learning), at some point it will no longer be possible to process further information. Hence, the present work extends conceptually the findings of Grossman and Stiglitz (1980) and shows how, even if information is free, information overload may occur causing a departure from the efficiency hypothesis.

Our contribution is important not only for investors but also for authorities. From the perspective of a policymaker, informative financial markets are essential to protect investors and ensure the economy functions well. The existence of speculative bubbles can drive asset prices away from their fundamental value, causing financial crises. Therefore, information overload should be limited, for example, imposing higher standards of transparency (Laud and Schepers, 2009) and increasing financial literacy of investors (Agnew and Szykman, 2010). The paper is organised as follows. Section 2 describes the concept of the efficient market hypothesis, the rational expectation hypothesis and the critique of Grossman and Stiglitz (1980). Section 3 presents the theoretical framework: we enlighten the limits of the rational expectations paradigm and discuss the importance of information overload for realistic models. Section 4 presents the model and its results. Section 5 discusses the implications of the model. The final section concludes the paper.

2. Are informationally efficient financial markets possible?

A market where prices fully reflect all available information is said to be "informationally efficient". Indeed, the Nasdaq glossary defines informational efficiency as: "*The degree to which market prices correctly and quickly reflect information and thus the true value of an underlying asset*". Generally, this is a starting hypothesis of many financial models, so that the expression "efficient market hypothesis" has been coined (EMH). We must emphasise that the EMH is not properly a model but a working hypothesis, our purpose is to explain why it may not work when considering information overload. Fama (1970) wrote that the three conditions that ensure market efficiency are:

(1) Absence of transaction costs in trading,

(2) Costless available information for every agent,

(3) Unanimous agreement on the implications of current information for the current price and distributions of future prices of each security.

These conditions are only sufficient and not necessary. So, if (2) is violated, it is sufficient that a number of investors can access the available information to ensure informational efficiency. The violation of (3) does not necessarily imply market inefficiency, except the case of investors who can systematically evaluate available information better than investors who use only information reflected in prices.

This hypothesis is often identified with the assumption of agents that obey Muthian or rational expectations (Muth, 1961), in the sense that "ex*pectations will be identical to optimal forecast (the best guess of the future) using all available information*" (Mishkin, 2004, p. 147), which means that forecasts can be wrong, but they will be the best ones using all disposable information. Following Mishkin (2004), given the variable X, the theory suggests

$$E(X) = X^{\mathrm{of}} \tag{1}$$

That is the expected value of X is equal to the optimal forecast implementing all the available information (X^{of}). If markets are efficient, all "unexploited profit opportunities" will be eliminated by investors often named "smart money" (Mishkin, 2004).

Grossman and Stiglitz (1980, p. 404) showed the flaw in this argument with a simple, but effective, consideration: the EMH states that prices reflect, at any time, all disposable information, but then informed traders cannot use information to earn a return. Therefore, why do they spend time and money in gathering information? With their model, Grossman and Stiglitz tried to explain that costless information is not a sufficient condition for informationally efficient markets, it is a necessary condition. If information is simply available for everyone and fully reflected in prices but has a cost, it is useless to attempt to make returns on it. This leads to uninformed trading.

3. Theoretical framework

3.1 From "Olympic" rationality to bounded rationality

The ultimate end of economic agents is always the satisfaction of human desires, which economically translates into the maximisation of a utility function. Muth (1961) criticised previous approaches, noting that the various expectations formulas proposed were not coherent with how the economy really works and suggested the *rational expectations paradigm*, that is "*an approach that assumes that people optimally use all available information—including information about current and prospective policies—to forecast the future*" (Mankiw, 2009, p. 582). This implies that agents may be wrong but over any long period, learning from past mistakes, on average they will be right. The rational expectation hypothesis was further deepened by Lucas (1972, 1976) and Sargent and Wallace (1975, 1976). The famous Lucas critique (Lucas, 1976) shows that economic policies cannot pursue the estimated targets because once they are implemented by the policy maker, agents will change their behaviour. It is possible to deceive economic agents in order to get the desired result, but as Abraham Lincoln said, "*you can fool all of the people some of the time, you can fool some of the people all of the time, but you can't fool all of the people all of the time*" (Friedman, 1975).

In 1979, Kahneman and Tversky proposed their prospect theory, showing several flaws in the traditional expected utility theory. Choices among risky prospects produce various effects that are inconsistent with utility theory. For example, individuals overvalue outcomes that are obtained with certainty in comparison with merely probable outcomes (*certainty effect*). The work of Kahneman and Tversky was an important step towards a new approach to economics: in a world where agents are not perfectly rational, the extreme assumption of a sort of "*Olympic rationality*" (Fagiolo and Roventini, 2012) becomes inadequate. Tversky and

Kahneman (1986) also criticised the idea that learning from errors will ensure that irrational decision-makers will be driven out by rational ones. Albeit learning and selection tend to improve efficiency, "*no magic is involved*", and the strict conditions required by effective learning are unrealistic.

Simon (1955) discussed the importance of reconsidering the idea of the "economic man", conceived by the traditional theory as completely aware of the relevant aspects of his environment (*global rationality*), in the light of the limited access to information and the true computational capacities of the human mind. Simon (1956, 1991) defined a new paradigm, called *bounded rationality*: decision makers often possess scarce information, they face evident computational limits and have limited time to decide; therefore, economic agents "*adapt well enough to 'satisfice'; they do not, in general, 'optimize'*" (Simon, 1956, p. 129) and, consequently, they often use rules of thumb.

One of the first models that proceeded in a different way from traditional economics was proposed by Arthur (1994). In the "El Farol Bar problem", agents decide whether to go to the bar every Thursday night. If too many agents go to the bar, it becomes too crowded and chaotic. The problem of the agent is to decide where she should spend the evening, conjecturing simultaneously what will be the choice of the other agents. Arthur presented a problem of bounded rationality given the presence of imperfect information and limited computational power.

Keynes already exposed the "not-too-rational" nature of investors in his "General Theory of Employment, Interest, and Money" (Keynes, 1936) suggesting that professional investors play a guessing game, similar to a common newspaper game (the so-called *beauty contest*) in which competitors have to guess the six prettiest faces from several photographs, choosing the one considered the more likely to be chosen by the other participants.

The reason of the success of traditional models relies on the fact that building models of rational and unemotional agents is easier than building models of "*quasi-rational emotional humans*" (Thaler, 2000); furthermore, a model with rational agents is more manageable than assuming a world populated by heterogenous agents. But as Thaler predicted, we are witnessing an evolution: from *Homo Economicus* to *Homo sapiens*.

3.2 Information overload: a realistic feature for a realistic model

Information gained a huge role in economics over years. The works of Akerlof (1970), Spence (1973) and Rothschild and Stiglitz (1976), among the vast literature on the issue, finally gave a prominent role to information in economics. However, in these works great emphasis is given to the nature of information *per se*, and little is said about how agents gather information and successfully use it.

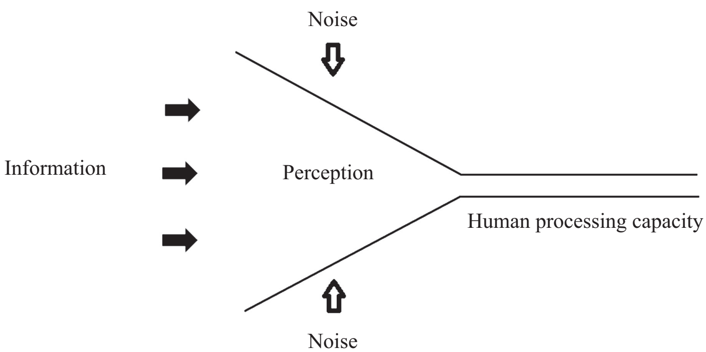
In the era of "big data", investors deal every day with a huge flow of information, therefore, an economic model must provide an explanation on how agents process this massive amount of data. The term "information overload" was popularised by Alvin Toffler in 1970 (Toffler, 1970) in his classic book "*Future Shock*". Information overload occurs when "*the amount of input into a system exceeds the processing capacity of that system*" (Milord and Perry, 1977, p. 131). The causes of this input saturation arise from the presence of too many inputs for the system to cope with, or because two inputs, say A and B, are presented successively such that both the inputs cannot be adequately processed. The system must set priorities to adapt and decide if it is the case to process A first and keep B in abeyance or sacrifice one input for the other (Milgram, 1970).

Several studies on the human brain provided evidence on our limited information elaboration capacity. Miller (1956) argued that every individual has a finite span of immediate memory estimated to be, for several reasons, about seven items in length. These considerations are the basis for the famous "magical number seven, plus or minus two" theory, which states that there is an upper limit of seven plus or minus two elements on our capacity to elaborate information. In a famous experiment carried out by Kaufman *et al.* (1949), random patterns of dots were flashed on a screen for 1/5 of a second and the individual's task was to count how many dots there were. On patterns containing up to five or six dots the subjects did not make errors, whereas the performance with more dots was very different. Below seven the subjects were said to "subitize"; above seven they were said to "estimate", that is what is called by Miller the "span of attention". What emerges from these studies is that individuals possess limitations (computational power, time, resources etc.). Klingberg (2000, p. 95) wrote that "*we can only retain a limited amount of information in working memory (WM), and when we try to perform several tasks at the same time, performance deteriorates*".

The model proposed in this paper (Section 4) is based on these considerations, but it is also deeply inspired by the original work of Shannon (1948), who posed as the fundamental problem of communication, the reproduction, either exactly or approximately, of a message from one point to another. He conceived communication systems as perturbed by noise, furthermore, any communication system presents a maximum rate of information that can be carried over a channel, known as channel capacity [1]. The "cognitive cone" (Figure 1) describes the process of acquiring information using these elements.

The idea is that an agent can perceive more information than he can process. Perception is represented by a cone whereas the shrinkage is the limited processing capacity of the human organism (which acts as the channel capacity); as in Shannon's model there is a source of noise. The representation of perception as a bigger entity than human processing capacity needs further explanation. We can consider an example (inspired by Kaufman *et al.*, 1949), and the reader can take part to this test. Figure 2a shows a square containing several dots, the task is to try to count the exact number of dots looking at the picture only three seconds. Someone will be able to guess the exact number, others will fail, but everyone can perceive the picture in its entirety. We can use the same rationale to show how information overload reduces our elaboration capacity and makes harder the task. Figure 2b works in the exact same way; with more dots and a more chaotic pattern we are still able to visualise correctly the entire picture, but now our guess is more the result of luck than of counting.

The argument seems to be obvious, but it is extremely important and less emphasised, especially in financial markets, where a massive amount of information is transmitted almost instantly (e.g. intra-day data). Too much information can also lead us to make wrong considerations. Using the same example (and a little bit of philosophy), if we fulfil the square entirely with black dots, and present the figure to an unaware individual, he will say that the



Source(s): Our elaboration

Figure 1.
The "cognitive cone"

image is a black square when, in reality, it is a square containing a certain, huge, number of black dots.

4. The model

4.1 The meaning of "infinite information" and the nature of information

Before presenting the model, it is important to clarify the meaning of the term "infinite". Indeed, in real-world analyses the concept of infinity is problematic (it could be debated philosophically, but this is not the place for such a discussion). Furthermore, there are many physical and biological arguments in favour of the fact that information is finite (for a discussion, see Fanelli, 2019). The argument is general and holds, *a fortiori*, for financial markets, where only a subset of the *omnibus information set* (the set containing all the existing information) is considered. So, when we talk of infinite information, operationally we mean an enormous amount of information. Nonetheless, for mathematical purposes (when proving Theorem 1) we need to consider information that approaches infinity.

The second point to clarify is what information is relevant in the analysis of financial markets. As pointed out by the anonymous referee, relevant information in financial markets includes trading information, corporate financial information, and corporate non-financial information. For the purposes of this model, with available information, and coherently with the assumptions underlying the EMH, we intend all the relevant information. This, conceptually, includes any kind of information that, if not disclosed to everyone, would generate profit opportunities. Even though mathematically we do not need to make a distinction in the forms of information, this distinction becomes relevant when discussing policy implications, for which we refer to Section 5.

4.2 Setup and assumptions

Definition 1. In an efficient market, prices always reflect all available information; this descents from the agents' rational expectations assumption. Therefore, a market will be considered efficient if: (a) all the agents use all available information, or (b) enough traders act fully informed.

For our purposes, in case (b) we do not need to quantify the number of operators acting fully informed.

Definition 2. Muthian or rational expectations hypothesis assumes that agents optimally use all available information (Mankiw, 2009).

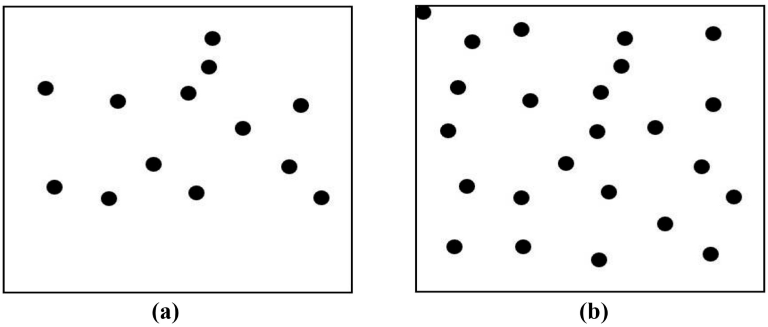


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Figure 2.
(a) Visual tests to show the discrepancy between perception and processing capacity. (b) How information overload reduces our processing capacity

Definition 2 mathematically translates into the following expressions:

$$R_s = R^{of} + \varepsilon \tag{2}$$

$$E[R_s] = R^{of} \tag{3}$$

with R_s the return on security s, R^{of} the rational expectation on R_s and ε a white noise process independent from the information possessed. (3) descents immediately from (2) taking the expected value to both sides.

Individuals will gather information only if they can use it to take better positions in the market than the positions of uninformed traders (Grossman and Stiglitz, 1980). We want to show that, even if the traditional assumptions hold, when information overload is considered, informational inefficiencies arise. Our purpose is to prove the following three conjectures.

Conjecture 1. When agents are endowed with Muthian expectations and information is costless, the EMH holds.

Conjecture 2 (extension of the Grossman-Stiglitz argument). Even if information is costless, when information overload occurs, markets may depart from the assumption of efficiency.

Conjecture 3. Even if information is costless, when information becomes "infinite" and overload occurs, markets are not informationally efficient.

In all the cases, we consider a market where all information is completely free and accessible (to avoid the Grossman-Stiglitz paradox), i.e. condition (2) holds (see Section 2) and there are no transaction costs (condition (1) holds). Finally, there is unanimous agreement on the implications of current information for the current price and distributions of future prices of any security (condition (3) holds).

Hypothesise that in this market an investment in a security s can yield a positive amount of dollars, W_s, with probability λ (probability of success), and a loss, L_s, with probability $(1-\lambda)$, such that the expected return from this investment is

$$E[R_s] = \lambda\, W_s - [1-\lambda]\, L_s. \tag{4}$$

If the EMH holds, λ should not depend on the information possessed because nobody should be able to use the available information to earn excess returns. Anyway, in order for investors to be fully informed, information should be "useful" even if costless. To avoid this impasse, we can think of λ as a subjective probability: investors will perceive the available information, i, as something useful to increase their probability of success, in particular we can model $\lambda(i)$ as a function with first derivative positive and second derivative negative, or $\lambda'(i) > 0$ and $\lambda''(i) < 0$. The idea is that the subjective probability of success is increasing at a decreasing rate because the first amount of information benefits the investor the most. Information, i, is a continuous variable with values between 0 and the maximum amount of information available in the market, i_{max}. For $i = 0$ an investor cannot succeed in the market because a minimal level of information is required to invest. Assume also that all the available information is "relevant" or there is no "bad" information, and that agents are risk neutral. We neglect, for simplicity, the role of noise in the transmission of information. The model is made by two periods: in $t = 0$ the agents choose simultaneously the level of information and in $t = 1$ we can observe two possible outcomes: the market is efficient, or the market is not efficient. For the moment we neglect the role of machine-based trading. However, we will show in Section 4.5 that with these assumptions, the model produces consistent results even in the presence of machine-based trading. Indeed, in the first scenario, when agents have infinite elaboration capacities, the addition of machine-based trading is useless; in the scenario with limited elaboration capacities, machine-based trading can help to overcome information overload but when information becomes "infinite", it becomes, again, useless because computers cannot store or elaborate "infinite" information.

4.3 Scenario with Muthian expectations

Proof of conjecture 1. Assume that agents are endowed with Muthian expectations; the expected utility of each trader deriving from investing in a security (we omit for simplicity the subscript s) can be written as

$$E[U(i)] = \lambda(i)\, W - [1 - \lambda(i)]\, L. \tag{5}$$

The maximisation problem and its solution for every trader are

$$\max_{i} E[U(i)] \Rightarrow E[R] = R^{of}. \tag{6}$$

QED. In this scenario every trader will choose a level of information equal to i_{max}, the maximum amount of information available, and will face $\lambda(i_{max})$. It is important to note that $E\,[U(i)]$ and $E\,[R]$ may differ because while $E\,[R]$ can be considered as how the "world" is, based on objective probabilities, $E\,[U(i)]$ is how investors perceived the "world", based on subjective probabilities. However, since traders take their investment decision considering all the available information, we have $E[R] = R^{of}$, where this equality follows tautologously from Definition 2. In this scenario traders act fully informed, which proves Conjecture 1.

4.4 Scenario with information overload

We introduce another function, $\xi(i)$, which models the capacity of a trader to elaborate information. This function is based on the "*cognitive cone*" (Section 3.2.), hence, we assume that $\xi'(i) > 0$ and $\xi''(i) > 0$, i.e. the information processing cost function (from now on, processing cost function) is increasing at an increasing rate. This function should be different for each trader: this introduces a source of heterogeneity among agents. This function reproduces the fact that cognition as the act of memorising, thinking, searching or obtaining the expertise of other agents is certainly costly (Tirole, 2015). The processing cost function is zero for $i = 0$, which is reasonable because if a trader has no information to elaborate, she will not suffer from processing costs. We do not need for our purposes to explicit the probability of success and the processing cost function.

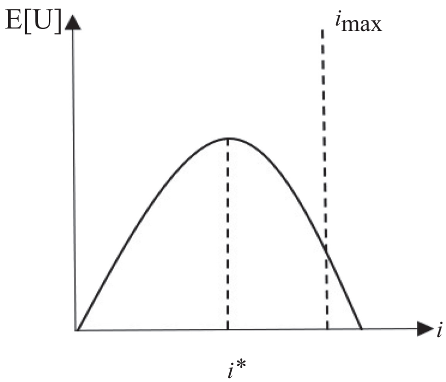
The new expected utility function (7) differs from (5) and incorporates this new unavoidable cost

$$E[U(i)] = \lambda(i)\, W - [1 - \lambda(i)]\, L - \xi(i). \tag{7}$$

With the new expected utility function (7), we are no longer sure that a trader will always use all the available information because the processing cost can cause the expected utility function to decrease before i_{max}. Figure 3 illustrates the argument: the processing cost causes the expected utility function to decrease before i_{max}. This trader, depicted in Figure 3, will not use all the available information because her optimal level of information is $i^* < i_{max}$. This idea is similar to the processing cost exposed in Persson (2018). In that context the decision-maker decides whether to process cues based on the cost $q_R > 0$, however, as she receives more cues, processes fewer, because her expected utility first increases and then decreases, as illustrated in this model. The existence of a reversed U-shaped relationship between the decision-making performance and the amount of information is also illustrated in the work of Roetzel (2018).

However, if for a sufficient number of investors i_{max} is lower than i^*, the EMH holds because these investors will act totally informed in order to maximise their expected utility function. This means that traders able to process information at low costs can ensure informational efficiency. This proves Conjecture 2.

Finally, we can mathematically state the result of Conjecture 3 as a theorem. We are going to prove the following



Source(s): Our elaboration

Figure 3. A possible expected utility of a trader affected by information overload

Theorem 1. Assume that the ideal conditions of an efficient market hold, i.e. (1)–(3) hold. Let also $\lambda'(i) > 0$, $\lambda''(i) < 0$, $\xi'(i) > 0$ and $\xi''(i) > 0$. If agents are risk neutral and endowed with an expected utility function of the form in (7), then as $i \to +\infty$, markets cannot be informationally efficient.

Proof.

As $i \to +\infty$, we have that

$$i \to +\infty \Rightarrow \xi(i) \to +\infty \tag{8}$$

$$i \to +\infty \Rightarrow \lambda(i) \to 1 \tag{9}$$

Given (8) and (9), we have also that

$$i \to +\infty \Rightarrow E[U(i)] \to -\infty \tag{10}$$

which means that, given the optimal level of information i_k^* for any k trader, with $k = 1, 2, ..., N$, and N the number of traders in the market, we will always have $i_k^* < i_{max}$, $\forall k$. Q.E.D.

The meaning of Theorem 1 is that as information increases, agents' processing abilities deteriorate to the point that no one will use all available information. If nobody acts fully informed, prices cannot reflect all the available information. This proves also Conjecture 3.

4.5 The role of machines and the relationship with theorem 1

We have to address now the role of computers in the light of the result of Theorem 1. Machine learning and artificial intelligence (AI) techniques have changed the way that data are elaborated, reducing complex tasks to few lines of codes. A rising body of literature has recently introduced the use of machine learning and big data analytics as effective tools to deal with economic problems (e.g. Athey, 2017, 2018). These tools, as argued in Section 5, can be used to reduce processing costs and may be effective instruments to ensure market efficiency.

However, the result of Theorem 1 holds even if we introduce computer-based elaborations. This derives from the fact that computers have limited capacity to store and elaborate information. Theorem 1 tells us that if the amount of relevant information increases "infinitely", no one will act fully informed. This is true even if machine-based techniques are allowed in the model because computers can deal only with a finite amount of information (a result deriving from the Bekenstein bound). It is true that in many real-world applications the use of these instruments is sufficient to ensure informational efficiency, nevertheless, the critique deriving from Theorem 1 is more subtle. We are showing that the theory is not logically well-founded. Indeed, with Theorem 1 we have shown that with two realistic features (overload and massive amounts of information), the EMH is unfeasible. Notice that this result does not need "infinite" information to hold, it suffices that the amount of information exceeds the computational capacities (both biological and technological) of the traders in the market. Having found this "philosophical" flaw in the EMH, which is mathematically demonstrated, is the main contribution of this work.

5. Discussion

With the model we have answered our initial question: do economic agents always use all the relevant information in their decisional process? The answer is clearly no. A first conclusion of the model is that informational efficiency, in the presence of massive amounts of data (non-redundant, qualitatively good and transmitted without noise), depends strictly on the nature of investors. If enough investors can elaborate information at low costs, the EMH may hold. It must be noted that this model is more than a model of financial illiteracy. Albeit educated individuals will exhibit better processing capacities, they remain humans with a maximum capacity of elaboration. The model also shows that when the amount of information becomes too big to be efficiently processed, the EMH ceases to be true, even if all the classical (and ideal) conditions of the model are respected.

Although the model can describe different situations of decision-making, it is applied to financial markets because they are the perfect environment for information overload. It is unlikely to find another market where information spreads in milliseconds and where decision-making must happen at fast rates. In financial markets more than in other markets the issue of efficiency and the consequences of information overload are indissolubly linked.

Which one of the two scenarios (investors able to process all the information or investors that suffer from overload) is more plausible? On one hand, one can argue that nowadays, with high-frequency trading, machine learning techniques and the growing number of specialised traders, the elaboration of data may suffer little of information overload. The use of algorithmic procedure consents to elaborate information in fractions of a second (650 microseconds) as they scan large datasets looking for the better opportunities (Spira, 2011). Beddington *et al.* (2012) think that the development of computer-based trading makes market prices more efficient, improves liquidity, and reduces transaction costs, thus making more reliable the hypothesis of an efficient market. On the other hand, someone may argue that it is practically impossible to fully handle all the information. For example, Saxena and Lamest (2018) note that the amount of available data to managers often exceeds their ability to effectively use these data, with the consequence that part of the information remains underused. We can surely assert that information overload affects a large proportion of investors, at least, those who are not sufficiently skilled. When investors face information overload, they tend to substitute complex strategies with heuristics. "*A heuristic is a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods*" (Gigerenzer and Gaissmaier, 2011); the problem with this kind of reasoning is that, if all traders act in this way, informationally efficient markets are not possible, and investors can take bad investment decisions.

There are few studies that consider the role of the phenomenon in finance; an important investigation was carried out by Agnew and Szykman (2005). The authors found that individuals with a low level of financial knowledge suffer from overload, which leads them to take the path of least resistance, the default option in defined contribution retirement plans, making very often the wrong investment decision. When decision makers are unable to make a mindful investment choice, they opt for the easiest alternative. It is exactly what happens when a customer can choose among a great variety of pizzas from a menu: she can spend a lot of time in examining every possible choice, take some "risk" trying a new pizza, or simply order a Margherita. Agnew and Szykman indicated three sources of overload in pension planning in addition to a poor financial knowledge: how information about alternatives is presented to the investors, the number of investment choices, and the similarity among the funds offered, because similar funds are harder to differentiate from each other. To avoid overload of investors and bad investment decisions, governments should invest into the financial education of individuals, which seems to be a good solution to moderate the phenomenon (Agnew and Szykman, 2010).

Information overload has also a role in explaining financial markets crises (Spira, 2011). The recent financial crisis derived from a financial industry that became too complicated to calculate adequately the risks of an investment. It is the case of the so-called "derivatives on steroids", or derivatives on derivatives. The more complex the derivative, the less transparent its risk evaluation process. This point is fundamental to orient the action of policymakers towards an incisive regulation of the financial industry, providing higher transparency standards (Laud and Schepers, 2009). Policymakers can intervene incisively in the regulation of corporate financial information, for example imposing higher standards of accounting transparency or imposing severe penalties for misconduct. On the other hand, not all types of information can be controlled by the policy makers, so the role of informed investors is crucial to ensure the well-functioning of financial markets.

Our conclusion is that the old notion of efficiency must be updated, maybe considering financial markets as governed by biological laws, where competition or interactions among the agents resemble the game of survival that biological organisms face (Lo, 2017). Conceiving agents as biological organisms and not as computers entails a better representation on how markets really work. The model here exposed can be made mathematically more complex and realistic considering other aspects interacting with overload, neglected in this work for simplicity. For example, information asymmetries, sources of noise in the transmission process or misleading information (e.g. fake news) can be contents of future works.

6. Conclusions

This paper shows the importance of including more realistic assumptions in economic modelling. Following the modern idea of agents with limited capacities (Simon, 1955, 1956, 1991; Kahneman and Tversky, 1979; Tversky and Kahneman, 1986; Arthur, 1994; Thaler, 2000) we have used the phenomenon of information overload to provide new insights into the possible causes of informational inefficiency. The agents that populate the model have limited processing capacity coherently with many studies over the human brain (Kaufman *et al.*, 1949; Miller, 1956). To sum up, our model can explain departures from the traditional assumption of informational efficiency introducing a processing cost function. This function, which is increasing at an increasing rate, introduces information overload: this occurs when the cost from elaborating another unit of information is not compensated by the increment of the positive part of the expected utility function. The assumption of individuals that use all the available information is far from realistic, especially when information is "too much". Agents choose the optimum level of information given their probability of success and their processing cost function; if the optimum is in correspondence of a lower level of information than the maximum amount available, then a trader will not act fully informed. As information increases, nobody will act fully informed and the EMH ceases to be true. This conclusion implies that: traders with low elaboration costs are most likely to act fully informed favouring efficiency; in the modern society of *big data* information overload becomes a recurrent phenomenon with the consequence that departures from efficiency are most likely to occur; individuals will use all the available information only when they can effectively handle it, this probably explains why very often traders prefer rules of thumb or the default option to complex investment strategies (Agnew and Szykman, 2005).

This framework can be extended in several ways. It is possible to add more realistic features, for example, what if we also include a distinction between "good" and "bad" information? What if we include a source of noise during the process of transmission? The issue can also be addressed using different approaches. For example, as suggested by the anonymous reviewer, the notion of endogenous risk is appealing because it does not need an "imperfectionist" assumption, such as costly information that acts as an imperfection in an otherwise perfectly efficient market. These are just a few suggestions for further development of the model.

Since it first appeared, the efficient market hypothesis has been considered the Gordian Knot of finance. We do not think that the market is "invincible", nevertheless, being able to continuously "beat the market" seems to be unlikely. The aim of the work is to criticise the use of the word "perfect" in association with something concerning human behaviour. Humans are not perfect, and so markets. Lo (2017, p. 113) wrote that "*our rationality is biologically too limited for the Efficient Market Hypothesis to hold at all times and in every possible context*", more than ever economic agents must face all their limitations: the old idea of informational efficiency and the paradigm of Olympic rationality cannot be considered still adequate to describe a world of "big" information.

Note

1. https://dictionary.cambridge.org/it/dizionario/inglese/channel-capacity

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