Asymmetric Implied Market Volatility and Terrorist Attacks

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Abstract

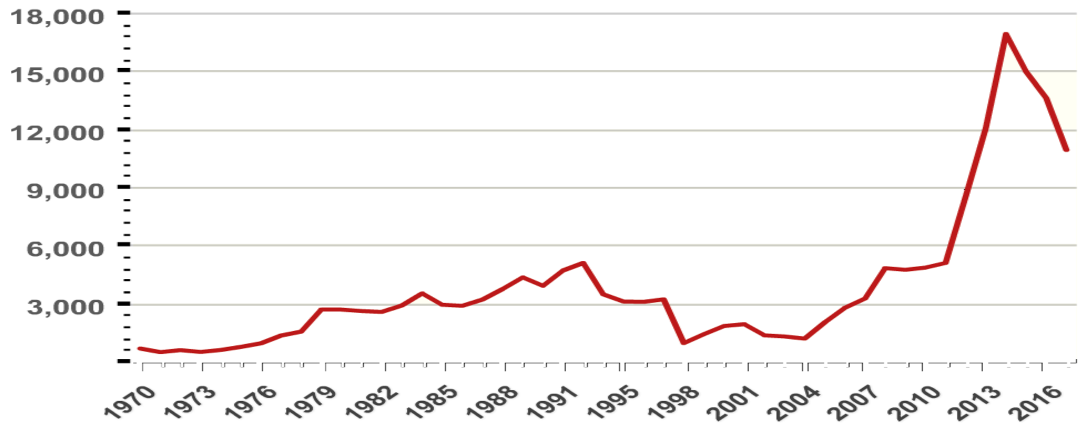
This paper studies the impact of terrorism on implied volatility in the U.S. financial market via an event study methodology. We decompose the options-based and forward looking VIX index into its negative (VIX^-) and positive (VIX^+) components, extracted only from put options and call options, respectively. This decomposition of the VIX index allows us to better investigate the asymmetric impact of terrorist attacks on implied volatility from the puts and calls channels separately. Our study finds evidence of a greater impact of terror detected for the puts channel of VIX , namely VIX^- . We further show that events that occur within the U.S. appear to impact both VIX and VIX^- in a similar way, whereas international terrorist attacks show a greater impact on the puts component, VIX^- . The calls component, VIX^+ , is found to be mainly detached from terrorist attacks.

Keywords: Implied Volatility, Terrorist Attacks, Asymmetric Volatility, Event Study

1 Introduction

With time, acts of terrorism evolve, not only in their sophistication, but also in their target types, lethality and frequency. In the aftermath of the Second World War, terrorism was very much driven by political doctrines with emphasis on military and governmental targets, however, by the end of the 20th century a virulent religious terrorism emerged, battling the globally expansive modernization that was thriving. This transformation also saw a shift to business and civilian targets, a novelty which shocked increasingly developed societies. Then came the unprecedented deadliest religiously motivated act of terrorism in the West, The Twin Towers (9/11), which saw the world as well as financial markets come to a halt, with the closures of the New York Stock Exchange and Nasdaq.

Figure 1: **Terrorist Incidents Over Time**



Notes: This graph shows the number of terrorist incidents over time. Source: `https://www.start.umd.edu/gtd/`.

The development of terrorism from a financial perspective has since gained worldwide interest. Understanding the reactions of markets and detecting patterns in their response provides invaluable evidence and insight into so many aspects of finance; from the behavioural and psychological analysis of investors, to the ongoing debates on market efficiency. Most studies have been linking terrorism with stock market indexes as proxies for market reaction (e.g. Abadie and Gardeazabal, 2003; Chen and Siems, 2004; Kollias et al., 2011; Wisniewski, 2016; Narayan et al., 2018; Papakyriakou et al., 2019) or have conducted research linking terrorism and proxies of realized volatility (e.g. Nikkinen et al., 2008; Arin et al., 2008; Essaddam and Karagianis, 2014). However, to date no research has been conducted on the impact of terrorism on the U.S. implied volatility index, the VIX index, well known for being a proxy for investors' sentiment and fear (e.g. Whaley, 2009).

We know today that investor sentiment can be a strong driving force of financial markets. Terrorist attacks have been found to be one of the main causes leading to changes in market sentiment and fear propagation among investors, which in turn will ultimately result in stock market declines (e.g. Burch et al., 2016; Papakyriakou et al., 2019). This may eventually lead to an increase in market volatility. In addition, given that investors are able to disclose in advance their expectations on the future level of the stock market in the U.S. by trading S&P 500 options, the VIX index may consequently be affected through the options market reflecting this information[1]. This paper therefore aims to provide an insight into the way investors react

[1]Since 2004 and 2006, the Chicago Board Options Exchange (henceforth CBOE) introduced derivatives on VIX , namely, futures and options respectively, the volume of which have increased dramatically given their

to and price these acts of terror by studying the ultimate effects on the VIX index.

Furthermore, we examine the asymmetric effect that terrorist attacks may have on the S&P 500 options underlying the VIX index. Motivated by a vast literature which has begun to decompose volatility measures (see Barndorff-Nielsen et al., 2010; Segal et al., 2015; Fu et al., 2016; Kilic and Shaliastovich, 2018; Bevilacqua et al., 2019), we first decompose the implied volatility index into its *positive* and *negative* components, namely, VIX^- computed by considering only S&P 500 puts, and VIX^+ computed considering only S&P 500 calls. Secondly, we contribute to this growing literature by showing the effect of terrorist attacks on the aggregate and decomposed VIX index by applying an event-study methodology to 17 significant terrorist attacks occurring across a number of developed countries over the past 18 years. Therefore our paper is the first study to, not only link terrorist attacks directly with implied volatility, but also with both its positive and negative components.

By decomposing the implied volatility allows us to determine the main channel, namely put or call options, through which acts of terrorism affect the financial market volatility index. Different volatility components have been found to be related with different economic states (e.g. Segal et al., 2015) and different portfolios of options with contrasting investors' sentiment and beliefs (e.g. Buraschi and Jiltsov, 2006). We believe that changes in investor sentiment and mood generating from terrorist attacks might be reflected asymmetrically in options trading and pricing.

These acts of terror are usually associated with the transmission of negative feelings and fear, increasing anxiety which in turn may affect investors' risk preferences (e.g. Kaplanski and Levy, 2010; Nikkinen and Vähämaa, 2010; Papakyriakou et al., 2019). Translated into options terms, different risk preferences would resolve in separate options trading; the equity index OTM puts play a key role as a shelter against equity market drops (Dennis and Mayhew, 2002; Han, 2008; Bondarenko, 2014), while equity index OTM calls are more commonly associated with optimistic beliefs (Buraschi and Jiltsov, 2006). Thus, we hypothesize that acts of terror should be reflected more on the puts side of the VIX (VIX^-). While the effect of terrorist attacks on the aggregate VIX index may be dampened by the positive component (VIX^+), thus causing it to be underestimated, by examining the negative component (VIX^-) allows us to correctly capture the effect of terrorist attacks on volatility. We further believe that the impact of terrorist attacks on VIX^- may also be the one that endures the longest in the trading

benefits in terms of hedging volatility risk.

days post event.

Through an event-study methodology we observe that, most of the time, VIX and VIX^{-} increase significantly on the event day and on the days following, whereas mixed results are found with respect to VIX^{+} , which in some cases is even found to decrease. The market resilience to terrorist attacks is also found to be asymmetric between VIX^{-} and VIX^{+} . Significant peaks in VIX^{-} continue to rise for a greater number of trading days following the attack, whereas a reduced effect in time is found for VIX , and almost no post-event effect is found for VIX^{+} . Robustness checks adopting realized volatility measures corroborate our findings.

The remainder of this paper is organized as follows. Section 2 reviews the related literature studying the impact of terror attacks on financial markets drawing the study hypotheses. Section 3 outlines the methodology employed in the paper with regards to both the decomposition of VIX and the event study. The data source and the event selection process are described in section 4. Empirical results are presented in section 5, and section 6 concludes the paper.

2 Related Research and Study Hypotheses

Over the years, the shift in the ideological motivation of terrorism has brought forth a change in the perspective of studies in this field. During the 1990s, the first few studies on the impact of terrorism were carried out in conjunction with the topic of tourism (see Sönmez et al., 1999) and politico-social effects (see Enders et al., 1990; Ginges, 1997). By the early 2000s, the focus of studies shifted to highlighting the negative impact that terrorism has on major economic variables including consumption and exports (see Eckstein and Tsiddon, 2004), and economic growth, as well as on the redirection of economic activity from investment spending towards government spending (see Blomberg et al., 2004). However, the events of 9/11 extended the scope of studies to the implications of terrorist activity on financial markets.

Abadie and Gardeazabal (2003) investigated the impact of the separatist group Basque Fatherland and Freedom (ETA) on stock prices in the Basque Country over the period 1998-1999. They estimated that as a consequence of two decades of terrorism in that region a loss of 10% of GDP was experienced. Kollias et al. (2011) examined the impact of the Madrid and London bomb attacks on their corresponding stock exchanges, finding similar reactions on the event day, however, different recovery periods subsequently. It has since been shown that stock market downturns during terrorist attacks are due to the uncertainty they cause, driving investor's attitudes. The significant stock price movements are a direct result of investor's increased conservatism due to the uncertainty present (e.g. Drakos, 2010).

The study of spillovers of the economic consequences of attacks from one nation's market to another has given rise to interesting results regarding the effect of terrorism on trade. By performing a study on the top 63 countries ranked by GDP, Kumar and Liu (2013) found that significant negative impacts are felt by trading partners when a country is the victim of terrorism, leaving non-trading partners completely unaffected. While trade is a channel for growth, it also enables the effects of terrorist attacks to propagate to other economies, intensifying its financial effects.

A country's politics can also influence the extent to which its market is affected by terrorism. Wisniewski (2016) studied the link between politics and its impact on stocks, arguing that while terrorism may at first glance be religiously motivated, religious and political interests can be seen as confounding in terror attacks. Their thorough literature review concluded that while stocks are affected by terrorism, the perception that such events are "one-offs" results in the effects remaining only in the short-term, with markets exhibiting the ability to rebound. A further study by Karolyi and Martell (2010) examining types of political landscapes and their effect on terror attacks on markets, showed that rich democratic countries are prone to a more negative market reaction. Narayan et al. (2018), through a dynamic conditional correlation study on eight OECD countries, were also able to show that the effects of terrorist attacks vary depending on whether the business cycle is in a contractionary or expansionary phase.

In addition, terrorist attacks are usually identified as one of the main causes of fear, shock and negative feelings among investors (e.g. Burch et al., 2016). Investor sentiment is one of the main channels through which these feelings and beliefs transmit to the stock markets (e.g. Papakyriakou et al., 2019). On a more general level, according to Kaplanski and Levy (2010), catastrophic events cause anxiety among investors affecting their investment behavior and risk preferences. While research on the effects of terrorism on historical volatility began emerging in the late 2000s, generally finding that the risk of terror incidents are significant in accounting for stock volatility (e.g. Arin et al., 2008; Nikkinen et al., 2008; Gulley and Sultan, 2009; Essaddam and Karagianis, 2014), there are currently no studies on the impact of terrorist attacks on implied volatility, even though the options channel has for some time been recognized as one of the main candidates for the transmission of investors sentiment and fear to the stock market.

In fact, changes in investor sentiment generating from terrorist attacks might be reflected in options trading and pricing as well as on the options underlying assets (e.g. Kaplanski and Levy, 2010; Nikkinen and Vähämaa, 2010; Papakyriakou et al., 2019). For instance, Nikkinen and Vähämaa (2010) found that terrorism had a strong adverse impact on stock market sentiment causing a downward shift in the expected value of the FTSE 100 index, leading to a significant increase in stock market uncertainty and to a more negatively skewed probability density function implied by option prices in the immediate aftermath of terrorist acts. Interestingly, with relation to the 9/11 terrorist attack, Poteshman (2006) detected an unusually high level of puts buying leading up to the event, a finding consistent with the widespread speculation post 9/11 that the terrorists, or their associates, traded ahead in the option market in anticipation, based on foreknowledge of the attacks.

According to Chesney et al. (2011), from an economic standpoint, terrorism is associated with negative effects such as a reduction of a country's resources, increased financial costs, and increased financial instability. It might also adversely affect a foreign company's investment (see Bekaert et al., 2014). Terrorist attacks are likely to cause financial stocks to decline in value reflecting negative investors' sentiment and fear surrounding the future (see Karolyi and Martell, 2010; Goel et al., 2017). Recognizing this thereby provides a normal backdrop for an increase in insurance demand. In the options market this is well known to be related to put options, where index OTM puts are traded for hedging purposes as insurance assets against equity market drops (see Bollen and Whaley, 2004; Han, 2008; Bondarenko, 2014). Therefore, a reasonable hypothesis may be as follows:

Hypothesis 1: *The negative component of the* VIX *index, namely* VIX^- *, is the one that may be more affected by terrorist attacks due to the fear and negative beliefs of investors reflected in puts trading.*

Furthermore we are also interested in the duration of the terrorist attacks impact on the options market, thus on the implied volatility. For instance, in relation to changes in the sensitivity of markets to terror incidents, Chen and Siems (2004) found that the U.S. markets have become significantly more resilient, namely in terms of the magnitude of their reaction and recovery rate. They attribute this to the provision of liquidity by the financial sector to stabilise markets. Ilalan (2017), built upon this through a more contemporary case study on France, Belgium and Turkey, putting forward a different explanation for the reduced sensitivity of stock markets to terrorism, suggesting that in countries where attacks are so frequent their "element of surprise" is less significant, the reaction of stock markets become negligible.

According to Karolyi and Martell (2010), quantifying the long-term economic impact of a given terrorist attack is not trivial. For instance, Becker et al. (2004) suggested that it may persist for some time in the psychological fear of terrorism, which in turn can affect economic behavior. Eldor and Melnick (2004) stated that the financial markets have not become desensitized to terror. Goel et al. (2017) stated that the role of electronic media amplifies the psychological impact of terrorist attacks, spreading outrage and anger more widely across countries. They questioned whether a possible desensitization of the public to terrorist attacks might be attributed to the rise in the number of terrorist incidents and excessive media coverage of these events, believing this to indeed be the case.

However, there exist discrepancies as to the length of time before which markets recover. The markets in developing countries appear to require much more time (e.g. Mnasri and Nechi, 2016), while European countries seem less affected. Kaplanski and Levy (2010) generally found that price reversals occur no more than 2 days after the terrorist event date in countries with stable economies. Therefore, one may conclude that the existing discrepancies are a mere result of regional specificities of the studies in question. Contrastingly, in the long-run markets appear to efficiently dampen the impacts of terrorism (see Barry Johnston and Nedelescu, 2006).

Conversely, with regards to financial market volatility, the picture appears to be even more blurred. Gulley and Sultan (2009) found that while volatility is indeed affected in some countries, such as Canada and Japan, on the whole markets seem robust and bounce back fairly quickly even from extremely fatal events of the likes of 9/11. Many later studies however tend to disagree with the claim of such resiliency in markets. Through the examination of the response of 53 markets to 9/11, Nikkinen et al. (2008) found that all regions experienced a significant increased volatility. Arin et al. (2008) performed a multi-country time-series analysis of the effect of terrorism on stock returns, interestingly pointing out that some countries, the U.K. included, appear less sensitive in terms of variance, though statistical significance of causality effects was found across all the sampled countries. Essaddam and Karagianis (2014) showed that the volatility of the stocks of some American firms tends to be abnormal on the terror event day, and remains so for approximately fifteen days subsequent.

Papakyriakou et al. (2019) affirmed that the extent of the stock market's reaction depends on how investors value terrorism-related information, and how investor sentiment changes after the attacks. This depends also on the post-event changes in the specific market, the effect on investors' sentiment and on risk preference. Drakos (2010) showed that the psychosocial impact of terrorist attacks may amplify their negative effects, and Becker et al. (2004) suggested that it may persist for some time and affect economic behavior.

Hence, in our paper, we are able to investigate whether or not by failing to account properly for changes in investors sentiment and risk preferences might be conveyed more strongly through the puts channel. Taking account of only aggregate volatility, as is the case with previous studies, might results in an underestimation of the effect that the event had on investor sentiment and fear. Especially during negative times and in response to such events, the impact of the psychological effect will be transmitted into put options trading for hedging purposes (Bollen and Whaley, 2004; Bondarenko, 2014), which in turn inflates the negative volatility component (VIX^-), possibly creating an asymmetric effect. Thus our second hypothesis is as follows:

Hypothesis 2: *The effect of terrorist attacks lasts longer in the puts-based* VIX^- *, compared to* VIX *and* VIX^+ *, with possibly higher volatility increases post-event.*

3 Methodology

3.1 Computation and Decomposition of Implied Volatility

The measure of implied volatility, the VIX index, is computed in this section following the CBOE (2009) methodology and notation. The VIX index is computed model-free from a set of out of the money (OTM) S&P 500 options and is an interpolation between the near and far term option maturities for each day in which it is calculated. It is, thus, a forward-looking volatility measure based upon changes over the next 30 days in the S&P 500 options price (both calls and puts). The implied variance is calculated as follows:

$$\sigma^2_{VIX_j} = \frac{2}{T}\sum_{i=1}^{n}\frac{\Delta K_i}{K_i^2}e^{rT}Q_t(K_i) - \frac{1}{T}\left[\frac{F_t}{K_0} - 1\right]^2 \tag{1}$$

where $i = 1, \ldots, n$ being the options strike price that is available on that specific date, T represents the expiration date, j is either (1) or (2), signifying the near or far term, respectively. K_0, the reference price, is the first exercise price less or equal to the forward level F_t ($K_0 \leq F_t$) and K_i is the strike price of i - OTM option, where if $K_i > K_0$ the option will be a call option, if $K_i < K_0$ a put option, and if $K_i = K_0$ it will be the average between call and put options. F_t is the S&P 500 forward price which is calculated from the Put-Call parity as

$F_t = e^{rT}[c(K,T) - p(K,T)] + K$.

The risk free rate with expiration T is given by r, and $\Delta(K_i)$ is the sum of the two closest strike prices to the exercise price K_0 divided by two. The implied variance in Equation (1) is built on the variance swap approximation shown by equation (2):

$$\sum_{i=1}^{n} \frac{\Delta K_i}{K_i^2} e^{rT} Q_t(K_i) \tag{2}$$

where $Q_t(K_i)$ represents a European call or put option price with a strike price respectively above or below K_0, the first strike price below F_0. In circumstances where $K_i = K_0$, the $Q_t(K_i)$ is the average between an at the money (ATM) call and an ATM put, relative to that strike price. So as to calculate the expected variance, an adjustment term is added to the expression in (2) to convert in the money (ITM) calls to OTM puts: $\frac{1}{T}\left[\frac{F_0}{K_0} - 1\right]^2$. See CBOE (2009) for further details on the VIX methodology.

The calculation of the VIX index is through the interpolation of the near and the far term variance, $\sigma^2_{VIX_1}(T_1)$ and $\sigma^2_{VIX_2}(T_2)$. These are the closest expirations to a 30 days average target in which monthly or weekly S&P 500 options are traded. The purpose of the VIX calculation is to better track the 30-days implied volatility in the equity market[2]. The VIX index always reflects an interpolation of two points along the S&P 500 volatility term structure, and it is calculated eventually through equation (1) as follows:

$$VIX_t = 100\sqrt{\frac{365}{30}\left[T_1\sigma^2_{VIX_1}\frac{N_2 - 30}{N_2 - N_1} + T_2\sigma^2_{VIX_2}\frac{30 - N_1}{N_2 - N_1}\right]} \tag{3}$$

We then follow the methodology of Bevilacqua et al. (2019) so as to compute both positive and negative components of VIX . More specifically, the following filters are applied on the K_i term in equation (1): for VIX$^+$ only S&P 500 call options are considered when $K_i \geq K_0$, and for VIX$^-$ only put options are considered when $K_i \leq K_0$. The first options sub-sample with strike prices above the reference price is defined as K_i^+ and the sub-sample below the reference price as K_i^-. The near and far term positive and negative variances are obtained by substituting K_i in equation (1) with both K_i^+ and K_i^-, respectively:

[2] In cases where the first month is not available or there are less than 3 days left for its expiration, the selected month is rolled onto the next expiration (third month), the reason for this is that if it was shorter the impact of volatility and volume can misdirect the calculation.

$$\sigma^2_{VIX_t^j} = \frac{2}{T}\sum_{i=1}^{n}\frac{\Delta K_i^j}{(K_i^j)^2}e^{rT}Q_t(K_i^j) - \frac{1}{T}\left[\frac{F_t}{K_0}-1\right]^2 \quad with \quad j=+ \quad or \quad -. \tag{4}$$

As a result, the implied volatility components VIX$^+$ and VIX$^-$ are given as follows:

$$VIX_t^+ = 100\sqrt{\frac{365}{30}\left[T_1\sigma^2_{VIX_1^+}\frac{N_2-30}{N_2-N_1} + T_2\sigma^2_{VIX_2^+}\frac{30-N_1}{N_2-N_1}\right]} \tag{5}$$

$$VIX_t^- = 100\sqrt{\frac{365}{30}\left[T_1\sigma^2_{VIX_1^-}\frac{N_2-30}{N_2-N_1} + T_2\sigma^2_{VIX_2^-}\frac{30-N_1}{N_2-N_1}\right]} \tag{6}$$

By extracting volatility solely from calls provides a proxy for *positive* implied volatility, whereas by extracting volatility solely from puts provides a proxy for *negative* implied volatility.

Other recent papers have extracted and decomposed implied variance from the options market in a similar way (e.g. Kilic and Shaliastovich, 2018; Feunou et al., 2017). They consider variance measures rather than volatility. In this paper we focus on the implied volatility measures, a direct proxy for both call and put options portfolios (see Bakshi et al., 2003)[3].

3.2 Event Study Methodology

An event study methodology is employed to assess every selected event's ability to cause abnormal returns (ARs) in the VIX indexes. Few papers have performed event studies explicitly observing the abnormal changes in volatility and not returns of assets or indexes referring to volatility changes as abnormal volatility (see Białkowski et al., 2008; Essaddam and Karagianis, 2014). These studies have specifically researched changes in volatility of returns. This is not the case in our paper. In terms of VIX , returns refer to the daily return of VIX considered as an asset, or alternatively can be seen as changes in daily implied volatility. Hence our research focuses on an index which is based on volatility, but not on the volatility of the index itself. Therefore, following the likes of other papers which have used indices as a proxy for markets (see Nikkinen and Vähämaa, 2010; Kollias et al., 2011; Chesney et al., 2011), we refer to our abnormal changes as abnormal returns (ARs).

ARs can be described as the difference between actual ex-post returns and expected returns, where expected returns are based on a predefined window of days before an event date. It

[3]The relationship algebraically is $(VIX)^2 \approx (VIX^+)^2 + (VIX^-)^2$ and therefore, after taking the square root for the volatility based measures, it will result in $VIX \neq VIX^+ + VIX^-$ given the nonlinear scale introduced by the square root.

follows that when AR = 0, actual ex-post returns are in line with expectations pre-event, and consequently no abnormality has ensued from the event being studied. This methodology enables the examination of the magnitude of positive and negative abnormal changes reflected through the direct assessment of the reaction of many market participants.

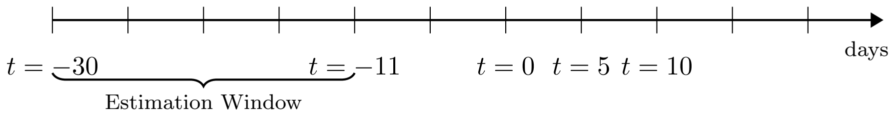
Since VIX represents changes in daily implied volatility, positive ARs point towards a heightened volatility in markets (where actual ex-post returns are greater than expected returns), and conversely negative ARs signify a drop in market volatility (where actual ex-post returns are smaller than expected returns). Following this context, we expect to see positive ARs after negative shocks of the likes of terrorist attacks.

Event studies are based upon the assumption of semi-strong efficiency in markets, implying that new information is immediately absorbed and reflected in market prices. Therefore, changes in the market can be accredited to the events which resulted in the announcement of the news in question. The framework for conducting an event study, specifically for this paper, is broken down into a series of steps outlined in the next subsections.

3.2.1 Timeline

We define the estimation and event windows by following the methodology employed by Chen and Siems (2004), Barry Johnston and Nedelescu (2006), Kollias et al. (2011) and Chesney et al. (2011). More specifically, we select a 20-day estimation window starting from 30 days prior to the event to 11 days prior (all in terms of trading days). It is often customary in event studies to leave a gap between the estimation window and the event window to avoid bias being introduced, for example, from potential leakages of information prior to the event date. The event date, denoted as t = 0, is taken as the first date of a terror act, whether the event lasted more than a day or not. If an attack occurred on a non-trading day, the following trading day is considered as the event date instead. Three event windows are tested: one comprising only of the event date itself, and the other two encompassing five and ten trading days following the event date, respectively. It is important to note however that the more days the event window includes, the more likely it is that other events may *contaminate* the results. Hence the length of an event window can be seen as a direct trade-off between analyzing the effect of an event on ARs and its validity.

Figure 2: Timeline



Notes: This figure shows a simple representation of the time line used in the event study analysis. t = 0 represents the event data or the day of the terror act, t = 5 represents the five trading days following the event date and t = 10 the ten trading days following the event date.

3.2.2 Abnormal Returns and Testing

The estimated return is the hypothetical return that would have occurred if the terrorist event had not taken place, as opposed to actual ex-post returns. It is computed as:

$$E(R_t) = \frac{1}{20} \sum_{t=-30}^{-11} R_t \tag{7}$$

where $E(R_t)$ is calculated over the 20 days in the estimation window, as in Kollias et al. (2011). The ARs are then computed via a mean-adjusted returns model, by subtracting expected returns $E(R_t)$ from the actual ex-post returns R_t as follows:

$$AR_t = R_t - E(R_t) \tag{8}$$

where $R_t = ln(\frac{P_t}{P_{t-1}})$, P_t being each of the volatility indexes (VIX , VIX$^-$ and VIX$^+$) price level at time t (or $t-1$ for P_{t-1}). In order to determine the statistical significance of ARs, we must compute the cumulative abnormal returns (CARs). CARs is calculated as the aggregate ARs over the event windows:

$$CAR_{(0,T)} = \sum_{t=0}^{T} AR_t \tag{9}$$

where T is the last day of the event window. Following the cross-sectional t-test procedure, outlined in Brown and Warner (1985), the significance of ARs can then be tested. The appropriate t-statistic is computed accordingly:

$$t - statistic = \frac{CAR_{(0,T)}}{\sigma\sqrt{N}} \tag{10}$$

It is necessary to determine whether ARs arise by chance or whether statistical inferences may be derived from the results. The null and alternative hypothesis are defined as $H_0 : CAR = 0$ and $H_1 : CAR \neq 0$. In the event that a CAR is found to be statistically significant, then we can conclude that the terror event tested has a significant impact on the VIX series and therefore the stock market, and vice versa. Lastly, the level of sensitivity of the markets over time can then be further observed by computing the number of days required for actual ex-post return levels to regain their estimation window average level.

4 Data and Defining Events

This section outlines the events selection process and sources 4.1, as well as the options data used to compute the implied volatility indexes 4.2.

4.1 Terrorist Events Selection

A terroristic event is defined as any successful attack where the number of casualties exceeded fifty, with casualties being defined as deaths and/or injuries resulting from a terrorist attack. The time period examined extends from January 2000 to December 2017.

The final filtering process of all historical attacks is through the selection of events that took place only in countries that are listed in the top 30 according to their GDP levels, that are politically stable and that are over developed, thus are drivers of global growth and such attacks can lead to an increase in uncertainty worldwide (see Kumar and Liu, 2013; Papakyriakou et al., 2019). When the U.S. stock market experiences a drop, economic and financial uncertainty tracked by VIX will increase, which in turn may propagate to other economies. As a result, studying the largest developed and stable economies, which have the greatest spillover capacity to other nations, is most appropriate in researching the effects of terrorism on volatility as a whole.

The terrorist attacks data is collected from the Global Terrorism Database, U.S. Department of Homeland Security, for the period 2000 to 2017 (`https://www.start.umd.edu/gtd/`), resulting in the selection of a total of 17 terrorist events, listed in Table 1. With respect to the 9/11 attack, the U.S. stock market remained closed until 17th September 2001, which in turn is taken as the trading date that is used for this event for the event study analysis. For all the other terrorist attacks which occurred during the week-end, the same rule will apply.

Table 1: **List of Terroristic Events**

Event Date	Country	Event Description	Deaths	Injuries	Terrorist Motive	Target Type
11/09/2001	United States	Twin Towers (9/11)	2996	8191	Religious	B, C, G, P & T
06/11/2001	Spain	Madrid Bomb Explosion	0	95	Political	G
17/11/2003	South Korea	Buan Riot	0	60	Political	Po
11/03/2004	Spain	Madrid Tube Bombing	192	1755	Religious	T
07/07/2005	United Kingdom	London Tube Bombing	56	784	Religious	T
22/07/2011	Norway	Mass Shooting	77	75	Political	G, C & P
15/04/2013	United States	Boston Marathon Bombing	3	264	Religious	C & P
09/08/2013	United Kingdom	Belfast Riot	0	56	Political	Po
13/11/2015	France	Paris Attacks	137	413	Religious	B, C & P
22/03/2016	Belgium	Brussels Airport Bombing	18	135	Religious	C, P & T
13/06/2016	United States	Orlando Nightclub Shooting	50	53	Religious	C & P
14/07/2016	France	Nice Driver Attack	87	433	Religious	C & P
19/12/2016	Germany	Berlin Driver Attack	12	48	Religious	C & P
22/05/2017	United Kingdom	Manchester Concert Bombing	23	119	Religious	B, C & P
03/06/2017	United Kingdom	London Driver Attack	11	48	Religious	C & P
17/08/2017	Spain	Barcelona Driver Attack	14	101	Religious	C & P
01/10/2017	United States	Las Vegas Shooting	59	851	Political	B, C & P

Notes: This table describes the nature of each event which fits the selection criteria in our study, including the exact event date of the attack, a brief description of the attack, the number of casualties (deaths and injuries), the motivation of the attack, and the type of target defined as B = Business, C = Citizens, G = Government, P = Property, Po = Police & T = Transportation.

4.2 Data and Decomposed VIX Measures

Daily S&P 500 options and index prices are collected from OptionMetrics and Bloomberg over the total time period ranging from 02-01-2000 to 31-12-2017. Table 2 shows the descriptive statistics of the decomposed VIX indexes. The average level of VIX^- is higher than the average level of VIX^+ , consistent with the finding that VIX^- is the main component of the VIX index (e.g. Bollen and Whaley, 2004; Kilic and Shaliastovich, 2018; Bevilacqua et al., 2019). The max values for all three indexes correspond to the 2008 global financial crisis. VIX presents the highest standard deviation, while VIX^+ the lowest. All indexes are right-skewed and leptokurtic.

Table 2: **Decomposed** VIX **Series: Descriptive Statistics**

	Mean	Median	Max	Min	Std. Dev.	Skewness	Kurtosis
VIX	19.79	17.73	80.74	6.05	8.70	2.07	9.94
VIX^-	15.90	14.26	65.92	4.82	7.04	2.29	11.33
VIX^+	11.61	10.24	46.83	3.25	5.26	1.69	7.49

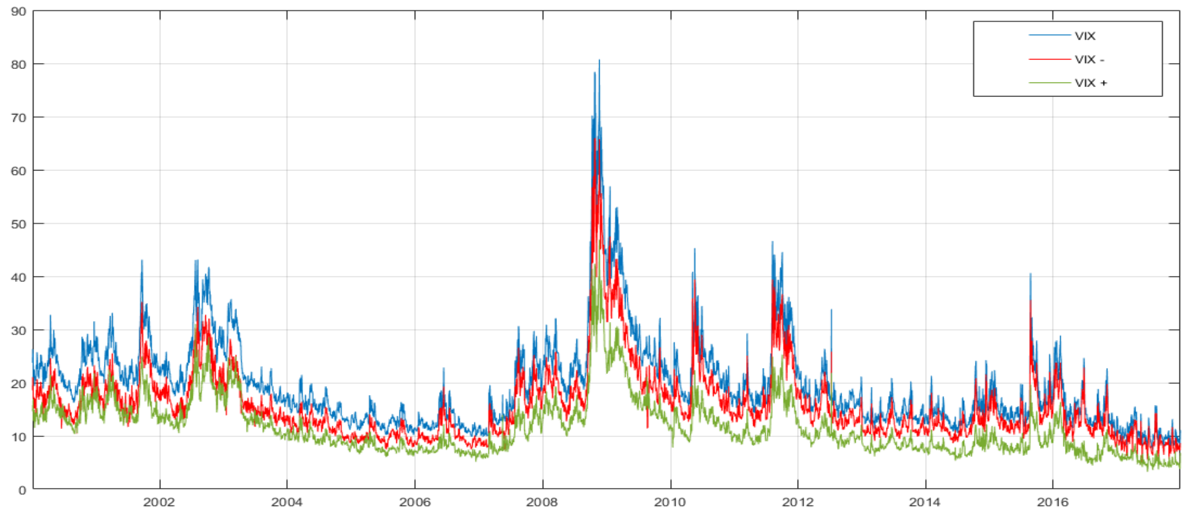
Notes: This table reports the main descriptive statistics for the VIX series, namely, VIX , VIX^- and VIX^+ during the period from 03-01-2000 to 29-12-2017, at daily frequency.

Figure 3 compares the VIX together with its positive and negative components[4]. The main spikes in the indexes correspond to all the main financial events including the dot-com bubble period, the 2001-2002 recession period, the 2008 global financial crisis, in particular the collapse

[4]Events such as the dot-com bubble, the 9/11 terrorist attack, the Iraq invasion, the 2008 global financial crisis and the Lehman Brother crash, the European sovereign debt crisis, the tension between Russia and Ukraine, the Chinese Yuan collapse and the Brexit vote, are only some of the various political, economic and financial events in the U.S. and worldwide which are included within our time period spanning from 2000 to 2017.

of Lehman Brother in September 2008, the two stages of the European sovereign debt crisis between 2010 and 2012, the Chinese Yuan crisis in mid 2015 and, finally, Brexit in June 2016.

Figure 3: **Decomposed Implied Volatility Series**



Notes: This figure shows a comparison between the VIX , VIX$^-$ and VIX$^+$ indexes during the period from 03-01-2000 to 31-12-2017, at daily frequency.

In general, VIX$^-$ is higher than VIX$^+$, with the opposite true only in rare circumstances such as bullish periods, characterized by optimistic investors' expectations and increased trading in call options (e.g. dot-com bubble period). We find that VIX$^-$ follows mainly the trend of VIX, especially when put options are more in demand as hedging strategies, and can be considered a proxy for downside risk. During negative times the S&P 500 puts are more expensive than the S&P 500 calls (Bondarenko, 2014) and puts are in more demand. VIX$^+$ reflects the component of volatility that is not dangerous for long equity investors (Segal et al., 2015) and can even be interpreted as "euphoria" (Bollerslev et al., 2015). Post global financial crisis, VIX$^-$ is always found to be higher than VIX$^+$, emphasizing the puts hedging role and investors' concerns regarding the possibility of another similar event occurring. Such results are in line with previous studies decomposing implied volatility or variance measures (see Kilic and Shaliastovich, 2018; Bevilacqua et al., 2019).

From Figure 3 we observe that 9/11 unequivocally triggered the greatest market reaction in comparison to other terrorist incidents, with a sharp incline in both components for some time post-event, while many other observed attacks appear to mostly peak on the actual event date. Overall, VIX changes are driven more by the negative volatility component (VIX$^-$) in comparison to the positive volatility component (VIX$^+$). This finding is in line with Bollen and

Whaley (2004) showing that investors weigh differently downside losses versus upside gains.

The VIX indexes are highly correlated in levels. For instance VIX is positively correlated at 0.97 with VIX^- and at 0.95 with VIX^+ . The two VIX components are correlated at 0.92 among themselves. These results are in line with previous studies (see Kilic and Shaliastovich, 2018; Bevilacqua et al., 2019). Even though the correlation among the VIX measures is high in levels, we take log changes in VIX indexes aiming to show how separate options portfolios, namely, calls and puts, might contain different information compared to the VIX alone and compared to themselves with regards to terrorist attacks.

5 Event Study Results

This section reports the results from testing firstly hypothesis 1, reporting the results for the event study analysis in relation to VIX in subsection 5.1, in relation to its components in subsection 5.2, and a robustness check in relation to realized volatility in subsection 5.3. Subsection 5.4 reports the results with respect the resiliency of market volatility to terror events over the years in order to check to hypothesis 2.

5.1 VIX Event Study Results

The statistical significance of ARs for the 0-day (event day), 6-day and 11-day event windows with respect to the VIX index is reported in Table 3. Statistical significance for the actual event date is found for 8 out of the 17 events studied. This is consistent with Chen and Siems (2004) who also found significance in the event day ARs for approximately half of their events. Not surprisingly, some of the largest event day ARs were experienced in the U.S., including 9/11, the Boston marathon bombing and the Orlando nightclub shooting. One would expect VIX to be significantly affected by these events given it is directly dependent upon the performance of U.S. companies. More specifically, event day statistical significance of abnormal volatility is consistent with the findings of Essaddam and Karagianis (2014) based on American firms.

Interestingly, of the three Spanish terror events analyzed, only the political 2001 attack carried out by ETA was found not to be significant on the event date. This could suggest that religious attacks appear to produce significantly more uncertainty, as an immediate reaction in the aftermath of the event, as compared to political ones. However, more plausibly, while Spain's 2001 political activism related directly to local conflicts of independence, the 2004 attack had international political repercussions, namely the withdrawal of Spanish troops in Iraq. This could certainly explain its significance on the U.S.'s economic and political situation, particularly given its own ongoing involvement in Iraq.

Moreover, among the largest significant event day ARs, comparable with the effect of the 3 aforementioned events on the VIX index, we find the Barcelona driver attacks in Las Ramblas in August 2017. While the Nice driver attack in France in 2016 was the first of its kind in Europe, followed by similar incidents in Berlin then London, none produced significant ARs. Curiously, the Barcelona driver attack however, which was the final incident of the same style in the sample occurring in late 2017, contrastingly exhibited strong positive ARs. The high and positive AR corresponding to the Barcelona attack suggests that events which occur in Spain have a global impact on market uncertainty, thus VIX . Since the ample agitation that Spain experienced due to struggles of territory, the country has known dramatic booms and busts, though in recent years has experienced steep and steady growth, seeing it return to its pre-recession peak by 2016, depicting the image of Spain as being an internationally safe country. The 2017 Barcelona incident evidently shattered this image, and produced a significant reaction among international investors, which could explain the brutal hike in volatility in the U.S. at that time.

Table 3: **VIX Event Study Results**

Event Date	Country	Event Description	Event Day AR	6-Day CAR	11-Day CAR
17/09/2001	United States	Twin Towers (9/11)	0.276***	0.203***	0.075***
06/11/2001	Spain	Madrid Bomb Explosion	-0.049	-0.094***	0.148***
17/11/2003	South Korea	Buan Riot	0.103***	0.086***	0.065***
11/03/2004	Spain	Madrid Tube Bombing	0.102***	0.008	-0.027*
07/07/2005	United Kingdom	London Tube Bombing	0.025	-0.079***	-0.026*
22/07/2011	Norway	Mass Shooting	0.006	0.412***	0.690***
15/04/2013	United States	Boston Marathon Bombing	0.369***	0.236***	0.238***
09/08/2013	United Kingdom	Belfast Riot	0.066*	0.206***	0.249***
13/11/2015	France	Paris Attacks	0.110*	-0.041*	0.108***
22/03/2016	Belgium	Brussels Airport Bombing	0.042	0.072*	0.185***
13/06/2016	United States	Orlando Nightclub Shooting	0.207***	0.073	0.332***
14/07/2016	France	Nice Driver Attack	-0.031	-0.106*	-0.178***
19/12/2016	Germany	Berlin Driver Attack	-0.018	0.116**	0.216***
22/05/2017	United Kingdom	Manchester Concert Bombing	-0.088	-0.100***	-0.054**
05/06/2017	United Kingdom	London Driver Attack	0.030	0.150***	0.042
17/08/2017	Spain	Barcelona Driver Attack	0.238***	0.063***	-0.062***
02/10/2017	United States	Las Vegas Shooting	0.056	0.117	0.204***

Notes: This table presents the VIX event study results. ARs and CARs are reported for the event day ($t = 0$), 6-day event window ($t = 6$) and 11-day event window ($t = 11$). The first column reports the first trading date after the terrorist attack, the second column the country of the attack. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Among all the events studied, 14 events are found significant for the 6-day window, many of which occurred outside of the U.S. Among these, the 2003 South Korean Riot injuring 60 people appears significant for all 3 event windows. As aforementioned, the U.S. was in the middle of a highly debated Iraq invasion at this time, with claims that this action was in fact illegal. It is evident that a high level of uncertainty was already present in markets contemporary prior to this event, which could explain the high positive ARs detected for this tumult in Asia.

All the 11-day event windows present fairly strong significant CARs. The greatest CAR, 0.690, was seen in late 2011 following the Norway mass shooting. While this marked the most fatal shooting since World War II in Western Europe, it is possible that such a significant AR could have been the result of a number of other concurring events. The European Sovereign Debt Crisis had been dramatically escalating since 2010 and was still ongoing by 2012. This turmoil saw markets severely decline across Europe by mid-2011. Simultaneously, Standard & Poor released a negative outlook on the U.S. credit position, downgrading its rating from AAA to AA+ over worries regarding the U.S. budget deficit, announcing a possible further downgrade in the future. These events injected tremendous uncertainty in the markets globally, which can be seen by the significant peak in VIX between 2010 and 2012 in Figure 3, and could very well explain why ARs were so significant and continuously rising (as seen by both the 6–day and 11-day CARs) for the Norway terror event.

When the terrorist attacks occur in a short period of time, e.g. in the same quarter, we observe that the implied volatility index barely reacts. This may be due to the fact that the financial market is either still recovering from the previous terrorist event, or it may be due to the fact that investors' attribute less importance to a terror event when this is of the same nature as the previous event. Kollias et al. (2011) tentatively explained that discrepancies in reactions from one terrorist event to the next could be explained by whether the event was a suicide attack or not, in that the threat no longer remains after the attack. In the case of the Manchester concert bombing in 2017, the perpetrator was indeed a suicide bomber, perishing in the attack and hence presenting no further threat after the event. Therefore, the markets may have responded in accordance to this fact, consistent with the insignificant AR shown in Table 3. In addition, the U.K. market has been found to be more insensitive than other countries to terror attacks (e.g. Arin et al., 2008), so we can further speculate that this event may have had a lesser impact on volatility than other events at that time due to the nature of its location.

On the subject of negative ARs, it is worth noting that the majority of 11-day CARs are negative, and significant for VIX . This shows that by the 10th day after an event, volatility has already begun to decrease. Once more, we supplement the findings that the U.S. has a more robust market compared to the rest of the world (see Chen and Siems, 2004).

5.2 Decomposed VIX Event Study Results

Table 4 shows statistical significance for the actual event day in 14 out of the 17 events studied with regards to VIX^- . There is a much greater significant terrorist attacks impact on the event day for VIX^- compared to the aggregate VIX .

On 9/11, the event day AR for VIX^- is found to be greater than that of VIX , and found to decline far more slowly post-event, implying a greater state of financial uncertainty than for the U.S. aggregate volatility index, and this continues over a greater length of time. However, it *does* appear that overall, ARs are much greater for VIX^- than VIX , suggesting that puts are extensively more affected by terrorist events than U.S. aggregate VIX . This is found to be true in every case in which the AR is significantly positive except only for the Orlando nightclub shooting and the Barcelona Las Ramblas driver attack.

Considering that the 9/11 attack on the Twin Towers was absolutely unprecedented in the West, it is not surprising that the aggregate market volatility was most impacted at this time. Moreover, it follows that as attacks became more frequent in developed countries, investors developed a certain, non-random, behavior towards these events which can explain why after 9/11 we start to see a stronger effect in the negative component of volatility, VIX^- . When negative shocks such as acts of terror hit the economy, it seems that investors have recognized the value in exploiting a future expected movement in implied volatility which would appear to arise through the put options channel. We can observe a shift in investment behavior in puts over time, a finding undocumented thus far. This is reinforced by the fact that 13 of the 6-day CARs and all of the 11-day CARs were found to be statistically significant, further showing how reactive puts are in the aftermath of an attack.

Corbet et al. (2018) stated that international acts of terror within Europe have less effect on stock market volatility, which is found to be true in our results when the aggregate VIX is considered only. However, when the volatility index is decomposed, we show that international acts of terror which occurred in Europe are able to significantly impact VIX^- in a more systematic way via the puts channel.

Results point towards the fact that events in the U.S. systematically have influence on both VIX and VIX^- . For instance, the 9/11 attack, the 2013 Boston marathon bombing and the 2016 Orlando nightclub shooting produced significant ARs for each window tested on both VIX and VIX^- . On the other hand, we find that when considering terrorist attacks in other countries, VIX^- is affected to a far greater extent. For instance, the Madrid bomb explosion, the London

Table 4: VIX^{-} **Event Study Results**

Event Date	Country	Event Description	Event Day AR	6-Day CAR	11-Day CAR
17/09/2001	United States	Twin Towers (9/11)	0.345***	0.257***	0.108***
06/11/2001	Spain	Madrid Bomb Explosion	-0.146**	-0.095***	0.186***
17/11/2003	South Korea	Buan Riot	0.127***	0.103***	0.120***
11/03/2004	Spain	Madrid Tube Bombing	0.116***	0.097***	0.091***
07/07/2005	United Kingdom	London Tube Bombing	0.108***	-0.064***	0.025**
22/07/2011	Norway	Mass Shooting	-0.020	0.416***	0.680***
15/04/2013	United States	Boston Marathon Bombing	0.375***	0.245***	0.249***
09/08/2013	United Kingdom	Belfast Riot	0.085**	0.211***	0.305***
13/11/2015	France	Paris Attacks	0.153***	-0.001	0.146***
22/03/2016	Belgium	Brussels Airport Bombing	0.164**	0.227***	0.330***
13/06/2016	United States	Orlando Nightclub Shooting	0.152**	0.249***	0.009**
14/07/2016	France	Nice Driver Attack	0.149**	-0.041*	-0.241***
19/12/2016	Germany	Berlin Driver Attack	-0.005	0.169***	0.323***
22/05/2017	United Kingdom	Manchester Concert Bombing	-0.129	0.119**	0.340***
05/06/2017	United Kingdom	London Driver Attack	0.152*	-0.043	-0.211***
17/08/2017	Spain	Barcelona Driver Attack	0.169**	0.034	0.091***
02/10/2017	United States	Las Vegas Shooting	0.150**	0.318***	0.439***

Notes: This table presents the VIX^{-} event study results. ARs and CARs are reported for the event day ($t = 0$), 6-day event window ($t = 6$) and 11-day event window ($t = 11$). The first column reports the first trading date after the terrorist attack, the second column the country of the attack. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

tube bombing, the Brussels airport bombing and the Nice driver attack, all produced significant ARs on the event day only for VIX^{-} . While VIX and VIX^{-} are highly positively correlated, a possible explanation for the difference in their volatilities response to terrorist attacks may be the fact that they are driven by different factors, with VIX^{-} more connected to geopolitical issues than VIX (see Bevilacqua et al., 2019), explaining its higher level of reactiveness. This shows how the negative implied volatility index is more sensitive to terror driven events which are found to be reflected more in puts trading.

Among the significant events, the Madrid bomb explosion exhibited a negative AR. This may actually suggest a decreased level of uncertainty, implying that other events had a greater driving force in influencing, namely lowering, volatility and fear sentiment encompassed in VIX^{-} at that time. This is inconsistent with the effect that terror events generally seem to have on financial markets, inducing positive abnormal volatility. A contrasting theory could be that as a result of terrorist attacks abroad, a greater sentiment of safety at home is felt since the terror event happened in another part of the world.

Our results reinforce this contrasting theory since only attacks abroad were found to exhibit negative ARs. This is further supported by Nikkinen and Vähämaa (2010) who used expected probability density functions to explain the behavior of markets post-attacks. Their findings show that after a terror attack, participant's reactions exhibit increased expectations of further acute movements in the market. Fears of further attacks are inevitably heightened after an act of terrorism, however investors, arguably irrationally, believe that their country, which is geographically removed, will be unaffected. This greater sense of security can be explained through increased security straight after attacks.

Table 5 shows the results with regards to VIX^+ . Statistical significance for the actual event date is detected in only 3 out of the 17 events studied. We observe how the calls portfolio is substantially less affected by ARs due to terrorist attacks. This is particularly consistent with Fu et al. (2016) who demonstrated that the negative relationship between portfolio returns and volatility is statistically insignificant when using the decomposed VIX extracted from out-the-money call options (VIX^+).

In addition, it is well known that put options are generally more expensive that call options (e.g. Bondarenko, 2014). The anomaly is often attributed to the fact that puts are frequently invested in as a downside hedge, particularly since it is more frequent for extreme movements in the market to be downwards rather than upwards (e.g. Bollen and Whaley, 2004). This phenomenon implies that when a negative shock of the likes of a terrorist attack hits the economy, there will be exceptionally more activity and sensitivity in puts than calls at this time, which further supports our findings. Hence, VIX^+ can be seen as the VIX component which dampens the effect caused by terror attacks on the aggregate implied volatility index.

The 9/11 attack is among one of the few events which still shows its effect on the VIX^+ . The stock exchange in the U.S. had closed following the 9/11 event, which in turn, not only influenced the stock market itself, but, consequently, the options written on the S&P 500 , both puts and calls. The discrepancy in the effect between VIX^- and VIX^+ following 9/11 can be explained by the fact that the panic felt on the event date transcended put options trades.

Interestingly, we also see that among the events which were significant, 2 were within the U.S., both at the 1% level, while the third was in Madrid but significant at 10% level. Moreover, all the events which were not significant for the 6-day and 11-day event windows were international attacks, except for one. We infer from this that VIX^+ is also less sensitive to events which occur abroad, unlike its counterpart VIX^- . This is consistent with Bevilacqua et al. (2019) who found that VIX^+ is mainly affected by macroeconomic variables including consumption, inflation and GDP, and therefore it follows that we would expect to see greater reactivity in the calls channel from terror shocks within the U.S. as opposed to internationally.

In Figure 3 we observe that VIX^+ is found to be more detached from the other indexes after the 2008 global financial crisis, whereas before the volatility indexes appear to move more in line with one another. This is reflected in recent years by the lower impact of terrorist attacks

Table 5: VIX^{+} **Event Study Results**

Event Date	Country	Event Description	Event Day AR	6-Day CAR	11-Day CAR
17/09/2001	United States	Twin Towers (9/11)	0.217***	0.138***	0.049**
06/11/2001	Spain	Madrid Bomb Explosion	0.090	-0.038	-0.045**
17/11/2003	South Korea	Buan Riot	0.064	0.059**	-0.009
11/03/2004	Spain	Madrid Tube Bombing	0.113*	-0.108***	-0.154***
07/07/2005	United Kingdom	London Tube Bombing	-0.002	-0.042*	-0.037**
22/07/2011	Norway	Mass Shooting	0.009	0.342***	0.638***
15/04/2013	United States	Boston Marathon Bombing	0.246***	0.165***	0.187***
09/08/2013	United Kingdom	Belfast Riot	0.016	0.187***	0.171***
13/11/2015	France	Paris Attacks	0.099	-0.055**	0.092***
22/03/2016	Belgium	Brussels Airport Bombing	0.075	0.167***	0.271***
13/06/2016	United States	Orlando Nightclub Shooting	-0.020	-0.146	-0.207
14/07/2016	France	Nice Driver Attack	-0.142	-0.072	-0.057
19/12/2016	Germany	Berlin Driver Attack	0.018	0.231***	0.344***
22/05/2017	United Kingdom	Manchester Concert Bombing	-0.010	0.064	0.044
05/06/2017	United Kingdom	London Driver Attack	-0.012	-0.034	0.063
17/08/2017	Spain	Barcelona Driver Attack	0.021	0.142**	-0.047
02/10/2017	United States	Las Vegas Shooting	-0.069	0.099	0.191

Notes: This table presents the VIX^{+} event study results. ARs and CARs are reported for the event day ($t = 0$), 6-day event window ($t = 6$) and 11-day event window ($t = 11$). The first column reports the first trading date after the terrorist attack, the second column the country of the attack. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

on VIX^{+} ; there are no significant ARs on event days after the Boston marathon bombing in 2013. Lastly, we can observe how, most of the time, the AR signs of VIX^{+} are opposite to that of VIX^{-} showing that in the majority of the attacks VIX^{+} actually reduces. This is in line with the fact that VIX^{+} is considered as a proxy for good volatility, increasing with market exuberance, increasing with rising underlying prices and increasing during periods when the state of the economy is good (e.g. Kilic and Shaliastovich, 2018; Bevilacqua et al., 2019).

The nature of option trading post-financial crisis drastically changed as a direct result of a change in investor behavior and regulation. From previous shock crashes, such as the Great Depression, we know that the effects of investors fears on markets can remain for many years, with evidence that even generations born after a crisis remain less willing to take investment risks (e.g. Malmendier and Nagel, 2011). It is therefore without great surprise that after the 2008 financial crisis, market participants, including banks who became the subject of increasingly greater regulatory pressures, took less direction call option bets which saw a divide appear between VIX^{+} and its corresponding volatility indexes, VIX and VIX^{-} .

To conclude, we can confirm our first hypothesis given that the impact of the selected terrorist attacks on the two components of the VIX index, namely VIX^{-} and VIX^{+} , is found to be quite asymmetric and skewed towards the puts side of the options distribution. Investors fears and negative beliefs prevail following terrorist attacks thus reflecting their changing sentiment and mood in put options trades (e.g. Papakyriakou et al., 2019). Lower impact of terror acts on VIX compared to VIX^{-} is coherent with the interpretation that the VIX^{+} optimistic component of the U.S. implied volatility index may actually dampen the effect.

5.3 Decomposed Realized Volatilities and Terrorist Attacks

As a robustness check, we also investigate the impact of terrorist attacks on decomposed annualized realized volatility as introduced by Barndorff-Nielsen et al. (2010). We define the aggregate annualized realized volatility as:

$$RV = \sqrt{\frac{252}{n}\sum_{i=1}^{n} r^2} \tag{11}$$

where, r is the daily log difference in S&P 500 prices. We take n equal to a trading month, namely, 23 days. The realized volatility two components, namely, RV^- and RV^+ are computed as follows:

$$RV^- = \sqrt{\frac{252}{n}\sum_{i=1}^{n} r^2 1_{r<0}} \tag{12}$$

$$RV^+ = \sqrt{\frac{252}{n}\sum_{i=1}^{n} r^2 1_{r>0}} \tag{13}$$

where the RV^- is computed only from negative S&P 500 returns, and RV^+ only from positive S&P 500 returns over the previous n days. See Barndorff-Nielsen et al. (2010), Segal et al. (2015) and Bevilacqua et al. (2019) for more details on the methodology.

We believe that the decomposed realized volatility series should also react asymmetrically to acts of terror. We check this hypothesis as a robustness check against the main empirical results of this paper conducted on the implied volatility index, VIX and its two components.

We report the results in the appendix of the paper. We find that event studies on realized volatility and decomposed positive and negative realized volatilities (RV^+ and RV^- respectively) reveal a similarity with the VIX analysis. Likewise with VIX$^-$, RV^- is distinctly more reactive to terrorism than RV^+. Every RV^- 6-day and 11-day CARs is found to be significant, except for the 2017 UK London driver attack. RV^+ on the other hand exhibited 3 non-significant events for the 6-day CAR and 2 non-significant events for the 11-day window. In addition, 3 times more event-day ARs were found to be significant for RV^- compared to RV^+. While the asymmetry is less pronounced when it comes to decomposed RVs compared to the decomposition of VIX , results still evidently point to the fact that RV^- is more impacted by terror events. A notable difference is the large event day ARs and their significance at a 1% level for 9/11 in both the RV and RV^- series versus a very low and non-significant value in comparison for RV^+. The 9/11 twin-tower terror attack was very symbolic due to its unprecedentedness on many levels, including number of casualties as well as motivation of attack. For this reason, the difference in significance and AR amounts for this event is particularly indicative of RV^-'s higher level of reactivity to terrorism relative to RV^+.

Moreover, the fact that realized volatilities are affected, be it in less magnitude compared to implied volatilities, further confirms the importance of the options market as a channel through which market sentiment is transmitted onto the stock market following such acts of terror. Realized volatilities, on the other hand, are backward looking measures which take time to react after the selected events, and the impact occurs most of the time after a few days, this being mostly uncovered in 6-day and 11-day CARs.

As a final robustness check we undertake the exact same event study exercise through adopting implied variance measures, proxied by the square of our decomposed VIX series (see Kilic and Shaliastovich, 2018). As expected, the results hold and the asymmetry is still present when the square operator is applied to the volatility measures. More specifically, we find that the same events produce significant ARs and CARs as those of Tables 3 to 5. The size of the ARs and CARs differ, be it greater[5].

5.4 Market Resilience to Terrorist Attacks

In order to check our second hypothesis and thus to assess how the sensitivity of volatility to terror events has evolved, we compare the number of days required for the indexes to revert to their estimation window mean levels[6]. It follows that if the mean reversion rate decreases over the years, one could imply that financial investors are becoming desensitised to terror, and markets more resilient to terrorist attacks. In Table 6 we can observe a direct comparison of the days required for market recovery in response to the same selection of terrorist events for both VIX and for its components, VIX$^-$ and VIX$^+$.

We notice how after 9/11 the implied volatility indexes required the highest number of days to recover. More specifically, the aggregate VIX shows a convergence to the previous average

[5]We do not report the results of this robustness checks though the results are available from the authors upon request.

[6]When the event date is right before a week end or a stock market closure, an adjustment term equal to $P_0 + P_0(+/-5\%)$ is applied to take into account the week end effect to the volatility indexes' market resilience.

Table 6: **VIX Indexes and Market Resilience**

Event Date	Country	Event Description	VIX	VIX^-	VIX^+
17/09/2001	United States	Twin Towers (9/11)	71	104	45
06/11/2001	Spain	Madrid Bomb Explosion	0	0	0
17/11/2003	South Korea	Buan Riot	5	5	2
11/03/2004	Spain	Madrid Tube Bombing	13	18	12
07/07/2005	United Kingdom	London Tube Bombing	1	1	1
22/07/2011	Norway	Mass Shooting	1	1	1
15/04/2013	United States	Boston Marathon Bombing	14	15	6
09/08/2013	United Kingdom	Belfast Riot	5	1	1
13/11/2015	France	Paris Attacks	5	3	3
22/03/2016	Belgium	Brussels Airport Bombing	0	0	0
13/06/2016	United States	Orlando Nightclub Shooting	14	16	5
14/07/2016	France	Nice Driver Attack	0	0	0
19/12/2016	Germany	Berlin Driver Attack	0	0	0
22/05/2017	United Kingdom	Manchester Concert Bombing	0	0	0
05/06/2017	United Kingdom	London Driver Attack	0	4	0
17/08/2017	Spain	Barcelona Driver Attack	11	21	3
02/10/2017	United States	Las Vegas Shooting	0	0	0

Notes: This table presents the market resilience to terrorist attacks for VIX , VIX^- and VIX^+ . The days represent the number of days required for the volatility measures to converge to their estimation window average levels. The first column reports the first trading date after the terrorist attack, the second column the country of the attack, and the third column a brief event description.

level of 71 days, VIX^- required more than 100 days to go back to the pre- 9/11 index level, whereas VIX^+ recovered quicker taking 45 days.

The other events showing the longest recovery periods after 9/11 were the Boston marathon bombing and the Orlando nightclub shooting, both also U.S. attacks. All the other events, except for the Spain Madrid tube bombing and the Barcelona driver attack, have shown a relatively low sensitivity to the terrorist attacks in the post-event days echoing the findings of Chen and Siems (2004), who documented a consistent trend of higher resilience of the U.S. market to terror shocks. Contrary to Ilalan (2017), we believe that there is a linkage to other factors rather than simple expectation adjustments made by investors. We find that events occurring within the U.S. require a higher, though decreasing, number of days to recover from attacks than events abroad, implying that the event location has an impact on the speed of market recovery.

Interestingly however, terrorist attacks which occurred in Spain have also shown a high number of days to converge to the estimation window level. The Madrid tube bombing marked the first act of religious terrorism on civilians in a developed country since the Twin Towers, and the first religious attack of this magnitude in Europe altogether, which could very well explain the level of market disruption which we observe. Additionally, the Barcelona driver attack was the fourth of its kind in Europe in the space of a year. The context of this attack is therefore very relevant to the effect felt in the U.S. market, since, as put forward by Wisniewski (2016), politics and religion were undeniably in-differentiable at this time, heightening global tensions. Furthermore, Hon et al. (2004) found a fairly consistent strong correlation coefficient between Spanish and U.S. markets, not only in times of negative shocks, such as 9/11, but in normal times also, which reinforces the link implied by our results between these two economies.

Usually, VIX^- takes a greater number of days to converge to the average compared to VIX especially when the attacks occurred on U.S. ground. However, in the Paris and Belfast attacks VIX^- converged first. VIX^+ is found to be the implied volatility component which takes the least number of days, confirming how the calls channel is the one least impacted by terror. Overall, it does appear that as the years go by, the frequency with which markets require more than a day to recover is becoming slimmer. We find that our second hypothesis is confirmed for the majority of the most significant terrorist attacks. Furthermore, the frequency of terrorist attacks above the defined level of fatality has seen an increase over the years, with eleven out of the seventeen events concentrated in the second half of the sample period. Yet, in conjunction with this observation, the level of VIX variation became far smaller towards the end of the period, a time when terrorism became more recurrent. This increased stability in the fear index could very well be a sign of a greater *desensitisation* of the U.S. financial markets to terror.

Finally, with respect to the realized volatility measures, overall we find that RVs take less days to return to their estimation window mean levels. For example, VIX required 71 days to bounce back after 9/11, while RVs only took 53 days. Interestingly, RVs do not exhibit pronounced sensitivity to the same events as the VIX indexes. For example, RVs require 0 days to reach their pre event mean for the Orlando Nightclub shooting in 2016, versus values of up to 16 days for the VIX indexes. While RVs exhibit a less sensitive behaviour than VIX , we still observe the same trend of desensitisation over our 17 year study.

6 Conclusion

This paper explores the effects of terrorism on implied volatility in the U.S. financial market via an event study methodology in order to shed new light on the asymmetric impact of terrorist attacks. We attempt to identify the main channel through which terrorist activities impact upon implied volatility by decomposing VIX into its positive and negative components, VIX^+

and VIX^- , extracted only from call and put options respectively.

We find evidence of a greater impact of terror detected for the puts component (VIX^-). Terror events occurring within the U.S. appear to impact similarly on both VIX and VIX^- , however international terrorist attacks impact more, through the puts channel, on the negative volatility index, VIX^- . We show that VIX and VIX^- have divergent initial reactions to terror attacks, as shows by event day ARs, which can reveal a great deal regarding the contrasts in investor behaviour in the U.S. Our findings also show that VIX^+ , extracted only from calls, appears to be the component least affected by terrorist attacks.

A robustness check adopting decomposed realized volatilities is also performed. We find that the asymmetric impact of acts of terror on RV^- is more pronounced compared to the aggregate RV and, especially RV^+. Overall RVs are less impacted by terrorist attacks compared to implied volatilities, emphasizing the importance of the options market as a main channel through which market sentiment, mainly investors' fear, is transmitted onto VIX indexes, mainly onto VIX^- extracted from put options.

Additionally, inferences have been made regarding the resilience of the implied volatility indexes. We show that VIX^- is the implied volatility component which presents less market resilience compared to VIX and VIX^+ . Discrepancies are detected with respect to the behaviour of the two VIX components in response to same terrorist events.

The value of VIX as a tradeable asset has traditionally been associated with hedging, or more recently as a response to trends and market shocks. This is the first study, to the best of our knowledge, which begins to assess the varying and asymmetric impact of terrorist attacks on different options portfolios, calls and puts, constituting the VIX index.

Future research should be conducted in this area to further explore the potential to utilize the volatility indexes as speculative tools in response to global terrorism, namely by exploiting differences in derivative returns between the different options (calls and puts) portfolios. The potential to further specify the conditions under which such directional and asymmetric bets could be systematically successful, for example, in terms of specific criteria belonging to any terror event, could in turn provide some sort of prediction as to what can be expected of market volatility following any event in question. A better understanding of the impact of specific acts of terror on different options types might represent an efficient tool in order to reduce the costs of terrorism, reduce the impact on the stock market and the potential market sentiment contagion.

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Appendix A RV Event Study Results

Table A1: **RV Event Study Results**

Event Date	Country	Event Description	Event Day AR	6-Day CAR	11-Day CAR
17/09/2001	United States	Twin Towers (9/11)	0.318***	0.639***	0.739***
06/11/2001	Spain	Madrid Bomb Explosion	0.023	0.040*	0.022
17/11/2003	South Korea	Buan Riot	-0.009	0.191***	0.275***
11/03/2004	Spain	Madrid Tube Bombing	0.088**	0.199***	0.354***
07/07/2005	United Kingdom	London Tube Bombing	0.037	0.295***	0.529***
22/07/2011	Norway	Mass Shooting	-0.024	-0.014	0.314***
15/04/2013	United States	Boston Marathon Bombing	0.304***	0.579***	0.725***
09/08/2013	United Kingdom	Belfast Riot	-0.130	0.296***	0.634***
13/11/2015	France	Paris Attacks	0.000	-0.176***	0.202***
22/03/2016	Belgium	Brussels Airport Bombing	-0.029	-0.097***	-0.124***
13/06/2016	United States	Orlando Nightclub Shooting	0.044	-0.163***	0.471***
14/07/2016	France	Nice Driver Attack	-0.022	-0.134**	-0.943***
19/12/2016	Germany	Berlin Driver Attack	-0.027	-0.149***	0.122***
22/05/2017	United Kingdom	Manchester Concert Bombing	0.002	-0.113***	-0.072**
05/06/2017	United Kingdom	London Driver Attack	-0.039	-0.027	-0.300***
17/08/2017	Spain	Barcelona Driver Attack	0.221***	0.367***	0.466***
02/10/2017	United States	Las Vegas Shooting	-0.005	-0.488***	-0.529***

Notes: This table presents the RV event study results. ARs and CARs are reported for the event day ($t = 0$), 6-day event window ($t = 6$) and 11-day event window ($t = 11$). The first column reports the first trading date after the terrorist attack, the second column the country of the attack. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A2: RV^- **Event Study Results**

Event Date	Country	Event Description	Event Day AR	6-Day CAR	11-Day CAR
17/09/2001	United States	Twin Towers (9/11)	0.469***	0.594***	0.658***
06/11/2001	Spain	Madrid Bomb Explosion	0.052	0.316***	0.441***
17/11/2003	South Korea	Buan Riot	-0.051	0.130***	-0.052***
11/03/2004	Spain	Madrid Tube Bombing	0.180***	0.253***	0.300***
07/07/2005	United Kingdom	London Tube Bombing	0.036	0.224***	0.458***
22/07/2011	Norway	Mass Shooting	0.005	0.213***	0.964***
15/04/2013	United States	Boston Marathon Bombing	0.629***	0.936***	1.153***
09/08/2013	United Kingdom	Belfast Riot	0.108	1.096***	1.542***
13/11/2015	France	Paris Attacks	0.173	0.474***	0.796***
22/03/2016	Belgium	Brussels Airport Bombing	0.200	-0.188***	0.132***
13/06/2016	United States	Orlando Nightclub Shooting	0.076***	-0.183***	1.034***
14/07/2016	France	Nice Driver Attack	-0.040	-0.257***	-2.089***
19/12/2016	Germany	Berlin Driver Attack	0.032	0.189***	0.529***
22/05/2017	United Kingdom	Manchester Concert Bombing	0.020	0.133***	0.243***
05/06/2017	United Kingdom	London Driver Attack	0.003	0.015	-0.027
17/08/2017	Spain	Barcelona Driver Attack	0.354***	0.422***	0.510***
02/10/2017	United States	Las Vegas Shooting	-0.719***	-0.605***	0.510***

Notes: This table presents the RV^- event study results. ARs and CARs are reported for the event day ($t = 0$), 6-day event window ($t = 6$) and 11-day event window ($t = 11$). The first column reports the first trading date after the terrorist attack, the second column the country of the attack. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3: RV^+ **Event Study Results**

Event Date	Country	Event Description	Event Day AR	6-Day CAR	11-Day CAR
17/09/2001	United States	Twin Towers (9/11)	0.013	0.770***	0.898***
06/11/2001	Spain	Madrid Bomb Explosion	0.004	-0.116***	-0.167***
17/11/2003	South Korea	Buan Riot	0.025	0.365***	0.429***
11/03/2004	Spain	Madrid Tube Bombing	-0.002	0.155***	0.408***
07/07/2005	United Kingdom	London Tube Bombing	0.014	0.353***	0.520***
22/07/2011	Norway	Mass Shooting	-0.029	-0.193***	-0.522***
15/04/2013	United States	Boston Marathon Bombing	0.217	0.294***	0.415***
09/08/2013	United Kingdom	Belfast Riot	-0.270***	-0.233***	-0.017
13/11/2015	France	Paris Attacks	-0.097	0.033	-0.047***
22/03/2016	Belgium	Brussels Airport Bombing	-0.048**	-0.079***	-0.373***
13/06/2016	United States	Orlando Nightclub Shooting	-0.010	-0.150***	-0.286***
14/07/2016	France	Nice Driver Attack	-0.018	-0.010	-0.204***
19/12/2016	Germany	Berlin Driver Attack	-0.057	-0.360***	-0.548***
22/05/2017	United Kingdom	Manchester Concert Bombing	-0.002	-0.431***	-0.350***
05/06/2017	United Kingdom	London Driver Attack	-0.054	-0.050	-0.523
17/08/2017	Spain	Barcelona Driver Attack	-0.067	0.226***	0.299***
02/10/2017	United States	Las Vegas Shooting	-0.058	-0.605***	0.510***

Notes: This table presents the RV^+ event study results. ARs and CARs are reported for the event day ($t = 0$), 6-day event window ($t = 6$) and 11-day event window ($t = 11$). The first column reports the first trading date after the terrorist attack, the second column the country of the attack. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.