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Riding the swaption curve

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ABSTRACT

We conduct an empirical analysis of the term structure in the volatility risk premium in the fixed income market by constructing long-short combinations of two at-the-money straddles for the four major swaption markets (USD, JPY, EUR and GBP). Our findings are consistent with a concave, upward-sloping maturity structure for all markets, with the largest negative premium for the shortest term maturity. The fact that both delta–vega and delta–gamma neutral straddle combinations earn positive returns that seem uncorrelated suggests that the term structure is affected by both jump risk and volatility risk. The results seem robust for macroeconomic announcements and the specific model choice to estimate the risk exposures for hedging.

1. Introduction

Previous research in equity and fixed income strongly supports the market price of volatility risk to be negative for both markets. In contrast, investors trade volatility very differently in these markets. The commonly used trading instrument in the equity market is the variance swap (Carr and Wu, 2009), which pays the difference between realized variance and a benchmark variance rate that is set at the start of the contract.[2] On the other hand, institutional investors in the fixed income market hardly use variance swap contracts, but are very comfortable trading over-the-counter (OTC) swaptions to get volatility exposure. An important reason behind this might be a lack of clear benchmark points for volatility trading in the fixed income market. This is illustrated by a gap of 20 years between the introduction of the VIX in 1993 (Whaley, 1993) as a benchmark in the equity markets and the recent introduction of the SRVX index as the first interest rate-based volatility index (Mele and Obayashi, 2012). Only recently, equity variance swaps have been generalized to the fixed income market by Trolle (2009), Mele and Obayashi (2013), Mueller et al. (2013), Li and Song (2013) and Trolle and Schwartz (2014). This is most likely because of the 'non-trivial design issues' (Li and Song, 2013) and a lack of public data due to the OTC market structure. This might explain why, apart from Mueller et al. (2013), these studies focus on studying and replicating variance swap contracts at a single maturity and pay little attention to the term structure of the volatility risk premium. However, swaptions naturally give rise to a maturity term structure.[3]

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[2] See Carr and Wu (2009) for a detailed discussion on variance swaps in equity markets.

[3] A seemingly related, but nonetheless unrelated, line of previous work studies riding strategies on the yield curve instead of the swaption volatility curve. Yield curve-riding strategies are popular investment approaches for fixed income managers to achieve additional returns and have been widely documented; see for example the study of Dyl and Joehnk (1981). Basically 'yield curve-riding' or 'rolling down' strategies buy longer-dated bonds and sell before maturity. When these bonds approach maturity and the yield curve is upward-sloping, they will be valued at a lower yield. A profit will be realized when the bond is sold at the higher price. In contrast to these yield curve-riding strategies, this study is the first empirical research on the significance of long-short straddle combinations that 'ride' the swaption curve. Riding the swaption curve and riding the yield curve thus have in common that their respective forward curves are not realized over time.

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This paper complements the literature by a comprehensive empirical analysis of the term structure in the volatility risk premium for the four major swaption markets (USD, JPY, EUR and GBP).[4] We build on Low and Zhang (2005) who relate the volatility risk premium to straddle returns by proving that the average return of a delta-neutral straddle must not be zero if volatility risk is priced. We argue that conclusions can be inferred on the term structure of the volatility risk premium by studying the average return of a long-short combination of two delta-neutral straddles with different maturities. In particular, we study long-short straddle combinations which are either delta–gamma or delta–vega neutral. We are the first to apply these two strategies in the fixed income market. Hence, we provide results showing it is plausible that the delta–gamma and delta–vega neutral strategies can be linked to volatility risk and jump risk respectively, corroborating the equity market findings of Cremers et al. (2015). Since sellers of volatility risk might also desire a jump risk premium to compensate for sudden and extreme losses caused by the unexpected nature of jumps, we use this link to better understand our empirical results. The presence of a jump risk premium is not unlikely because there is evidence for the presence of jumps in interest rates. Johannes (2004) reports a significant impact of jumps on the pricing of fixed income derivatives on Treasury bills. Dungey et al. (2009) relate jumps in the fixed income market to the release of macroeconomic data and show that about 2/3 of jumps can be explained by these releases. Using variance swaps, Li and Song (2013) show in a recent paper, that jump tail risk is time varying in the swaption market.

Our research provides a number of new results. We use a large data set of at-the-money implied volatility quotes on the 10-year swap rate and 1 to 12-month swaption maturities between April 1996 and December 2011 to calculate the returns of the long-short straddle strategies. Our main finding is that we find statistically significant returns for all markets and for both delta–gamma and delta–vega neutral strategies. This finding is consistent with an upward-sloping term structure in the volatility risk premium implying a less negative premium for longer-term swaption maturities. The strategy returns consistently decrease across maturities, which suggests that the risk premium curve flattens for longer maturities. The low, although increasing, correlations between the delta–gamma and delta–vega neutral strategies, that is −23% for the 3 vs 6-month maturity strategy, −4% for 6 vs 9-month and 38% for the 9 vs 12-month, indicate that the two strategies are uncorrelated and probably capture different effects. This suggests that the term structure of the volatility risk premium is affected by both jump risk and volatility risk, especially at short-term maturities. In general, all these empirical findings are consistent across the four individual markets.

Second, it is important to recognize that our strategy is based on the Black (1976) model to estimate the risk exposures for hedging and to calculate the returns. To assuage this concern, we re-run our strategies on the Vasicek (1977) model for all markets and on the stochastic volatility model proposed by (Hagan et al., 2002) for the vega neutral strategy in the USD market.[5] The Hagan et al. (2002) model is also known as the Stochastic Alpha Beta Rho (SABR) model. In the Vasicek (1977) framework we find comparable summary statistics to our main findings for all markets. The vega neutral returns under the SABR model seem, in general, comparable to the returns under the Black model. For example the 3 vs 6-month strategy has a return (Sharpe ratio) of 0.89% (0.60) under the SABR model and 0.85% (0.54) under the Black model. Additionally, we do robustness checks of our findings on the 2-year swap rate and the USD swaption smile, we analyze the impact of macroeconomic announcements, and we empirically check the exposure of the strategy returns to the underlying swap rate.

Third, we study the economic importance of our results. For example, the average return across the four markets for the 3 vs 12-month delta–gamma neutral strategy is 1.89% (t-stat = 4.33) and an annualized Sharpe ratio of 1.35. The delta–vega neutral strategy reports a return of 1.14% (t-stat = 3.69) and an annualized Sharpe ratio of 0.95. However, after calculating break-even costs and comparing these with expected trading costs, we conclude that the returns of the strategies are not realizable by investors and therefore are not economically significant. This corroborates the findings for equity option strategies obtained by Santa-Clara and Saretto (2009).

Our paper relates to several strands of literature. Most importantly our study is directly related to the literature on the volatility risk premium in fixed income. Earlier studies, such as Goodman and Ho (1997) and Duarte et al. (2007), examine the presence and sign of the volatility risk premium in the fixed income market by analyzing the returns of a delta-hedged investment strategy. Since then, Almeida and Vicente (2009) have studied the volatility risk premium of fixed income Asian options, and Fornari (2010) has studied the volatility risk premium by calculating the difference between the implied volatility and forecast of realized volatility using a GARCH model. Recently, a growing body of literature which explores variance swap contracts in fixed income markets is emerging. Variance swap contracts provide model-free estimates of the variance risk premium because no assumptions are made about the price process of the underlying swap rate. Trolle (2009) studies the variance risk premium in the US Treasury market by estimating variance swaps under simplifying assumptions and concludes that the variance risk premium is negative. Merener (2012) studies a variance strategy on forward swap rates. Mueller et al. (2013) and Mele and Obayashi (2013) both analyze variance contracts on Treasury futures. Mele and Obayashi (2013) mainly focus on the theoretical derivation of the contract. Mueller et al. (2013) introduce a variance contract that is robust to jumps and can be replicated in the market at daily frequency. This approach helps them to empirically analyze the variance premium across the maturity and tenor spectrum, and leads them to conclude that the variance risk premium is negative, but less negative for longer maturities (increasing in maturity), and more negative for longer-term swap rates (decreasing in tenor). We see our work complementing theirs, because our data is on swaptions which is a different market, we focus on a straddles trading strategy and we make a distinction between volatility and jump risk. Trolle and Schwartz (2014) and Li and Song (2013) both study variance swaps in the swaption market and both have large and proprietary 'swaption cube' data sets from different providers that include data along three dimensions: swap tenors, swaption maturities and strike rates. Li and Song (2013) focus on jump risk and conclude that jump risk is time varying, while Trolle and Schwartz (2014) study variance and skewness risk premiums which are reported to be time varying and negative.

Our paper is also related to the strand of literature on test design for the existence of volatility risk premia. An important contribution in this field includes Branger and Schlag (2008) who provide a detailed discussion on the limitations of hedging-based strategies. In particular, discrete trading and model misspecification may cause tests to yield unreliable results. Doran (2007) demonstrates that delta–gamma hedged option portfolios are less

[4] Straddles are typically used to speculate on future changes of volatility. A straddle has zero delta exposure at inception. Straddles comprise a combination of a call option (receiver swaption) and a put option (payer swaption) on a swap with the same maturity and the same underlying strike rate. A receiver swaption is a call option on a receive fixed swap where the swaption holder has the right to receive a fixed rate on a swap in the future. A payer swaption is a call option on a pay fixed swap (or a put option on a receive fixed swaption) where the holder has the right to pay a fixed rate on a swap in the future.

[5] The additional data which is required to estimate the SABR model is not available for other markets.

subject to these discrete trading and model misspecification problems than traditional delta-hedged portfolio tests. Since we construct our long-short straddle combinations so that they are either delta–gamma or delta–vega neutral, our strategy returns are most likely less prone to the limitations raised by Branger and Schlag (2008).

Finally, our paper is related to Aït-Sahalia et al. (2012) who study the term structure of variance swaps in the equity market and reveal a significant jump component embedded in the variance swaps, especially at short-term maturities. Their analysis leads them to the conclusion that the variance risk premium is negative, becoming more negative for longer maturities, but we do not find this result in the fixed income market.

The remainder of the paper is organized as follows. Section 2 addresses our methodology and Section 3 describes the data. Section 4 presents our main empirical findings for the delta–gamma and delta–vega hedged long-short straddle combinations. Section 5 provides a robustness and sensitivity analysis on the efficiency of the delta-hedge, scheduled macroeconomic announcements, choice of the pricing model and additional data sets. Section 6 discusses the economic importance of our results and we conclude in Section 7.

2. Methodology

Straddles are commonly used to speculate on, or to hedge for, future volatility changes because they give exposure to volatility and have no exposure to the underlying. In this study we analyze long-short combinations of at-the-money swaption straddles with different maturities. The purpose of this section is to describe the valuation of swaption straddles, the method to calculate the straddle risk parameters and to determine the hedge ratios for long-short straddle combinations that are either delta–gamma or delta–vega neutral.

2.1. Computing straddle returns

A swaption straddle is a combination of a payer swaption plus a receiver swaption, both with the same exercise level.[6] In order to value the straddle we follow market practice and use the Black (1976) pricing model to convert quoted implied volatilities into straddle prices (Chaput and Ederington, 2005). To do so, consider a specific payer swaption giving the right to pay the fixed swap strike rate (F_X) and to receive the floating rate in a swap contract that will last n years (the tenor), starting in T years (the maturity), with m coupon payments per year and principal L. Let $t_i = T + i/2$ be the times of each of the coupon payments. Then, the contribution of the value of each individual cash flow (coupon payment) of the underlying swap to the swaption is:

$$V_{cf,i} = \frac{L}{m} e^{-r_i t_i} [FN(d_1) - F_X N(d_2)] \quad (1)$$

where F is the forward swap rate with the same maturity as the swaption, N is the cumulative normal distribution function, $d_1 = \frac{\ln(F/F_X) + \sigma^2 T/2}{\sigma\sqrt{T}}$, $d_2 = d_1 - \sigma\sqrt{T}$ and $r_i t_i$ is the spot rate that corresponds to the maturity of cashflow i at t_i. The sum of the values of the individual cash flows determines the total value of the payer swaption (V_p):

$$V_P = \sum_i V_{cf,i} = \frac{LA}{m} [FN(d_1) - F_X N(d_2)] \quad (2)$$

where $A = \sum_i e^{-r_i t_i}$. Here the presumption made by Black (1976) is that the forward swap rate follows a geometric Brownian motion (dW) where the volatility is a constant:

$$dF_X = \sigma F_X dW, \ F_X(0) = f \quad (3)$$

The value of a corresponding receiver swaption giving the right to receive strike rate F_X and pay the floating rate in a swap contract is equal to (V_R):

$$V_R = \frac{LA}{m} [-FN(-d_1) + F_X N(-d_2)] \quad (4)$$

The value of a straddle, S, (both long receiver and long payer swaption) with the same strike rate F_X is given by the sum of Eqs. (2) and (4):

$$S = V_P + V_R = \frac{LA}{m} [F(2N(d_1) - 1) - F_X(2N(d_2) - 1)] \quad (5)$$

Notice that the Black model is a model and therefore does not necessarily have a perfect fit with empirical data. The basic premise of a constant volatility is not supported by market dynamics, because swaption implied volatilities tend to vary for different strikes and swaption maturities (swaption smile). We discuss our data set later, but at this stage we emphasize that we only have swaption smile data for the USD and not for the other markets in our data set. As such we assume a horizontal smile and rely on the Black model (Black, 1976) to convert implied volatility quotes into prices. We will use USD swaption smile data for a robustness analysis in Section 5.4.

We calculate the return of a straddle as follows. Let S_t be the value of a particular straddle position at time t. Then the return of holding the straddle position, including funding costs, during the period from $t-1$ to t is:

$$R_t = \frac{S_t - S_{t-1}\left(1 + \frac{\#Days_{t,t-1}}{360} ir_{t-1}\right)}{L} \quad (6)$$

where ir_{t-1} is the annualized floating interest rate that is paid to borrow money to buy the swaption straddle position for the period from $t-1$ to t which comprises $\#Days_{t,t-1}$ number of days. In calculating the returns we ignore the bid-offer spread as well as impact of margin that would be required to back the straddle trades and limit the ability to leverage. Since trading costs and collateral requirements can be substantial for short option positions, as shown by Santa-Clara and Saretto (2009), we separately analyze the economic importance in Section 6. In this section we also discuss how the swaption market changed after the Global Financial Crisis (GFC) in 2008.

2.2. Calculating the risk parameters

Next to the valuation of the swaption straddles we also want to estimate the associated risks for hedging purposes and exposure analysis. These risk parameters are collectively known as the 'Greeks' and quantify the influence of changes in market factors on the straddle value. Using the Black model, the analytical delta, gamma and vega can be obtained in closed-form formulas (Martellini et al., 2003).

Delta (Δ), describes the price change of a straddle with respect to the underlying swap forward rate. Technically speaking it is the first derivative of the straddle price with respect to the swap forward rate:

$$\Delta = \frac{\partial S}{\partial F} = \frac{LA}{m} [N(d_1) - N(-d_1)] \quad (7)$$

At inception an at-the-money delta-neutral straddle position has a delta equal to zero according to the Black model. This means that the straddle value is not sensitive to a small change in the

[6] At inception, the ATM swaption strike rate is set equal to the swap forward rate.

underlying swap forward rate. Straddle exposures to the other Greeks are, however, not zero.

Gamma (Γ) is the second derivative of the straddle to the underlying swap forward rate and is the rate of change of the delta to the underlying swap forward rate:

$$\Gamma = \frac{\partial S^2}{\partial F^2} = \frac{LA}{mF\sigma\sqrt{T}}[N'(d_1) + N'(-d_1)] \quad (8)$$

where N' is the probability density function of the normal distribution.

Vega (υ) is the sensitivity of the straddle price to the implied volatility. In fact a straddle is quite vulnerable to volatility changes. Technically, vega is the first derivative of the straddle price with respect to the volatility parameter σ:

$$\upsilon = \frac{\partial S}{\partial \sigma} = \frac{LAF\sqrt{T}}{m}[N'(d_1) + N'(-d_1)] \quad (9)$$

Note that under the assumptions of the Black model vega is a comparative statistic and not a sensitivity to a variable that is dynamic such as delta or gamma.

We use the Black model in this study because of limitations on data availability for the EUR, GBP and JPY markets. However, just because financial markets quote implied volatility in the Black framework does not imply that risk parameters should be calculated from the Black model without an adjustment for the presumption of constant volatility across strike rates. Hence, as discussed by Levin (2004), the return distribution of swap rates is not necessarily lognormal as assumed by the Black model. We use USD swaption smile data for robustness analysis in Section 5.3 and 5.4 and show that our results are robust.

2.3. Specification of the hedging-based strategy

Low and Zhang (2005) relate the volatility risk premium to straddle returns by proving that the average return of a delta-neutral straddle must not be zero if volatility risk is priced. Following Low and Zhang (2005) we argue that studying the returns of a long-short combination of delta neutral straddles with different maturities will enable us to analyze the difference between the volatility risk premium across swaption maturities. Then, the obvious question is: what should be the ratio between the two straddles? In the spirit Cremers et al. (2015) we construct two combinations which are orthogonal and either exposed to volatility risk (delta–gamma neutral combination) or to jump risk (delta–vega neutral combination). This approach does not only enable us to analyze the term structure of the volatility risk premium but we might also be able to infer conclusions on the drivers of the term structure.

A long-short straddle strategy constructed to be delta and gamma neutral is vega positive and would be subjected to volatility risk but almost not impacted by jump risk. Since gamma is not constant in time to maturity we can construct the delta–gamma neutral strategy using the Black risk parameters. The strategy consists of two positions (i) a short position in 1 delta-neutral straddle contract with maturity T_s and (ii) a long position in Q_{ls}^{gamma} delta-neutral straddle contracts with maturity T_l with $T_s < T_l$. Q_{ls}^{gamma} is chosen such that the long straddle position creates an overall position in the long-short straddle combination that is not only delta but also gamma neutral (Eq. (8)):

$$Q_{ls}^{gamma} = \frac{\sqrt{T_l}\sigma_l F_l}{\sqrt{T_s}\sigma_s F_s} \quad (10)$$

where T_s is the swaption maturity, σ_s is the implied volatility and F_s the swap forward rate of the short straddle position and T_l, σ_l, and F_l are the swaption maturity, the implied volatility and the swap forward rate of the long straddle position respectively. The shorter dated swaptions have larger gammas such that the number of straddles bought to offset the gamma exposure of the short position is more than 1 ($Q_{ls}^{gamma} > 1$). This results in a positive vega exposure for the long-short combination because vega is increasing in time to maturity such that the shorter dated straddle has a smaller vega than the longer dated straddle. Doran (2007) also emphasizes the importance of controlling a delta hedged portfolio for gamma exposure to enable a more precise inference on the volatility risk premium.

Analogously, a long-short straddle strategy constructed to be delta and vega neutral is gamma negative and would be subjected to jump risk but almost not impacted by volatility risk. Since vega is not constant in time to maturity we can construct the delta–vega neutral strategy using the Black risk parameters. The strategy consists of two positions (i) a short position in one delta-neutral straddle contract with maturity T_s and (ii) a long position in Q_{ls}^{vega} delta-neutral straddle contracts with maturity T_l with $T_s < T_l$. Q_{ls}^{vega} is chosen such that the long straddle position creates an overall position in the long-short straddle combination that is not only delta but also vega neutral (Eq. (9)):

$$Q_{ls}^{vega} = \frac{\sqrt{T_s}F_s}{\sqrt{T_l}F_l} \quad (11)$$

Since the shorter dated straddle has a smaller vega, the number of straddles bought to offset the vega exposure of the short position is less than 1 ($Q_{ls}^{vega} < 1$). This results in a negative gamma exposure because shorter dated swaptions have larger gammas.

In the remainder of this study we analyze the profitability of these long-short straddle combinations for various swaption maturities. The long-short portfolio is formed at month end and rebalanced monthly in the spirit of Broadie et al. (2009). Intra-month, we neither change the two straddle positions nor delta-hedge the long-short portfolio using the underlying swap forwards. All risk exposures that get into the straddles during the month are supposed to cancel out as a result of offsetting long and short straddle positions. Notwithstanding, we do analyze the risk exposures on a daily basis in Section 5.1.

We follow Bakshi and Kapadia (2003) and Low and Zhang (2005) to apply a t-test for testing the null hypothesis that the long-short profit or loss is zero. We adjust the t-statistics according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation. Positive average returns of the strategy would suggest that the volatility risk premium for the shorter term swaption maturity is higher than the longer-term maturity. There would be evidence for a downward-sloping term structure in the volatility risk premium if the long-short returns show positive returns along a range of subsequent long-short straddle maturities.

3. Data and volatility risk premium

In this section we first describe our data set. We then provide empirical estimates of the volatility risk premium across different swaption maturities.

3.1. Data description

We use an extensive data-set of swap forward rates and swaptions that we obtain from Bloomberg and an anonymous major broker dealer. The advantage of two data sources is that this enables cross-checking to get a high quality data-set. If available we use Bloomberg data, otherwise broker data. The Bloomberg data are based on the most recent trades and quotes from multiple pricing sources for each country, among other ICAP which is the largest inter-dealer broker in the swap rate derivative market

Trolle and Schwartz (2014). We may therefore expect the quotes to be timely and accurate. Given the average swaption trading volume in excess of USD 150 billion notional, we assume that the Bloomberg data represent quotes that can be traded in practice.

Our sample covers the four largest and most liquid swap markets and spans a period of almost 16 years, from April 1996 to December 2011. Daily close prices (midpoint) of the implied Black volatility are available for at-the-money (ATM) swaptions with maturities of one, three, six, nine and twelve months for USD, EUR, JPY and GBP swaptions.[7] Before 1999 the EUR data are based on Germany, the most liquid fixed income market in the European Monetary Union. Bloomberg only provides ATM data because ATM swaptions are actively quoted in the market. Data on other strike rates is proprietary and broker dealer specific.[8] Furthermore, we focus on the 10 year swap tenor because swaption contracts for this maturity are the most liquid.[9]

Fig. 1 plots the time series behavior of the implied volatility of 3-month swaptions and shows that its' values have varied greatly over the course of the sample. We make two observations. Firstly, markets seem to show common moves with spikes during major stress events in the market in 1998 (unwinding LTCM), 2001 (bursting IT bubble and subsequent recession), 2008 (Lehman Brothers default) and 2011 (FED announced a stimulus policy that was called Operation Twist). Secondly, we note historically high values for the Japanese implied volatility in 2003. This jump is related to the sharp rise of the 10-year swap rate in Japan. On June 12th, 2003 the Japanese 10-year swap rate had an all time low at 0.43%. One month later it had more than doubled to a level at about 1%, while the rate further increased to 1.5% in September. The sharp increase was aggravated by many Japanese banks who were forced to sell government bonds due the limits on their value-at-risk; see BIS (2003) for more details.[10]

Table 1 reports the summary statistics of the swaption data across different maturities. We report the mean, standard deviation, skewness, kurtosis, minimum, and maximum for the month end implied volatility quotes in our sample. The number of monthly observations in each series is 189. We make several observations. The average volatility of Japanese swaptions is about twice as high as the volatility of the other three markets, as we already have seen in Fig. 1. Furthermore, implied volatilities for shorter maturities are higher and more volatile than for longer maturities in all four markets. This higher standard deviation gradually decreases for longer maturities. Finally, we also notice that the range between the minimum and maximum is the largest for the shortest maturities and narrows when maturity goes up. Together, this illustrates a higher risk embedded in shorter maturity swaption contracts. Low and Zhang (2005) argue that this higher risk warrants a decreasing volatility risk premium in maturity.

So far, we analyze the data separately and do not address the issue of commonalities between the four markets. To address this question we compute the correlations between the swap yields and between the implied volatilities. Table 2 presents the correlation between pairs of monthly changes in the swap yield (below diagonal) and between pairs of monthly changes in the implied volatility (above diagonal). We can observe a strong and positive correlation (0.70–0.79) between the monthly changes in the USD, EUR and GBP swap rates, indicating that these markets comove strongly. We make a similar observation for the 1-month change in the implied volatilities. In a similar vein we document a weak relationship between these three markets and the JPY market. The 0.15 correlation between the monthly changes of the USD and JPY implied volatility is a good example of this. This latter result suggests that the JPY swap rate and implied volatility move rather independently from the other three markets.

A potential concern about our data set could be that the data characteristics suggest that the assumptions of the Black model are violated. It seems that implied volatilities are not log-normally distributed and that jump dynamics are probably in play. The counterfactual on Black does not influence its ability to follow market practice and convert implied volatility quotes into prices but may influence the effectiveness of hedging on basis of the Black model. To alleviate concerns on the hedge ratios we analyze the robustness of our results when the Greeks are based on the Vasicek (1977) model and on a stochastic volatility model (SABR) in Section 5.3. Moreover, implied volatility from the Black model tends to have a negative correlation with the underlying swap rate (Chan et al., 1992). This might impact the delta-neutrality of our straddles. We work with the constraints of the data by investigating delta-neutrality in Section 5.1.

3.2. Delta hedged straddle returns

Using our swap forward and swaption data, we empirically examine the compensation for volatility risk following the method proposed by Bakshi and Kapadia (2003) and Low and Zhang (2005), based on gains/losses by a delta-hedged strategy. We compute daily delta-hedged returns of swaption straddles for various maturities and re-sample the returns at a monthly frequency. After one month the straddle and swap forward position will be closed and a new straddle will be initiated. It is important to note that we have a holding period of one month for all maturities, whereas most academic studies either limit their analysis to a single short maturity (1-month) or study hold-to-expiration effects. In our view, hold-to-expiration returns for maturities longer than one month raise issues that complicate the interpretation of straddle returns vs the maturity. The main issue is that hold-to-expiration returns for maturities larger than one month overlap and might bias any analysis on the relationship between the swaption maturity and the volatility risk premium.

Table 3 gives the summary statistics for daily delta-hedged straddle returns maturing in either 1, 3, 6, 9 or 12 months with a one month holding period. Not surprisingly the average hold-to-expiration returns for the 1-month maturity swaption straddles are negative for all markets and statistically significant at the 1% level for the USD, JPY and GBP swaptions. This result is consistent to those in Duarte et al. (2007), Fornari (2010) and Mueller et al. (2013) who also report average delta-hedged returns which are negative. Fornari (2010) also finds negative returns for Euro swaptions, which are not statistically significant. Second, for all markets we observe a term structure in the average returns which is similar. The term structure is upward-sloping with the largest negative return for the 1-month maturity. However, unlike Mueller et al. (2013) and Fornari (2010), who report negative volatility risk premiums across all swaption maturities up to 12 months, we find average returns which are positive for the longest maturities. A potential explanation for this is our one month rebalancing frequency against the hold-to-expiration set-up in the latter two studies.

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[7] At inception, the ATM swaption strike rate is set equal to the swap forward rate. We use the New York close, which is at EST 17:00, as the closing price for all four markets.

[8] In addition, our broker-dealer provides 5 strikes for USD swaptions (ATM, ATM ±50, ATM ±100). In Section 5.4 we use this USD data to test the robustness of our empirical findings.

[9] This is illustrated by the options on the 10 year U.S. Treasury futures contracts. Open interests and daily volumes of the options on the 2y, 5y and 30y futures contracts options are up to ten times lower than for the 10y futures. Source: CME Group, www.cmegroup.com.

[10] A similar but smaller effect can be observed in the U.S. data for the same period. The USD 10-year swap rate was at a low of 3.46% on June 13th, 2003 and rose back to about 5% in only two months due to mortgage hedging activity (see Duarte (2008)).

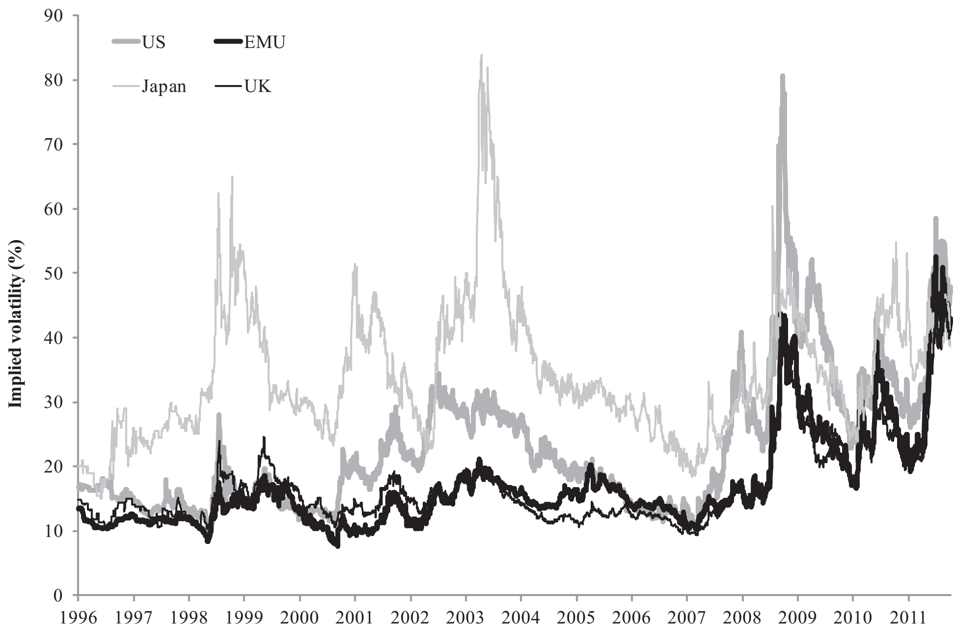


Fig. 1. Time series of swaption implied volatility. This figure shows the time series of the at-the-money Black's implied volatility of 3-month maturity swaptions with 10-year swap tenor for the USD, EUR, GBP and JPY markets. The sample period is from April 1996 to December 2011 and the EUR quotes before 1999 are implied volatility quotes for 3-month maturity swaptions on the German (DEM) swap rate.

Table 1
Summary statistics of swaption implied volatilities.

	Maturity (m)	Mean (%)	Stdev (%)	Skew	Kurt	Min (%)	Max (%)
USD	1	23.5	12.2	1.88	4.87	9.7	94.8
	3	23.2	10.8	1.53	2.97	10.2	80.6
	6	22.6	9.6	1.32	1.81	11.0	67.4
	9	22.1	8.9	1.25	1.44	11.3	61.4
	12	21.6	8.1	1.18	1.07	11.6	55.6
EUR	1	17.2	8.1	2.08	4.53	6.5	54.9
	3	16.9	7.5	2.02	4.21	7.6	52.6
	6	16.5	6.8	1.93	3.84	8.8	50.2
	9	16.2	6.4	1.87	3.57	9.4	47.8
	12	15.8	6.0	1.83	3.36	9.4	45.3
JPY	1	34.4	11.9	1.54	3.65	15.0	97.0
	3	34.3	10.3	1.23	2.68	15.0	84.0
	6	33.2	9.1	0.82	1.41	14.0	77.0
	9	32.1	8.2	0.64	1.04	14.6	71.0
	12	31.3	7.7	0.40	0.59	13.0	67.0
GBP	1	17.2	7.2	1.98	4.34	9.1	49.5
	3	16.8	6.4	1.98	4.35	9.3	45.9
	6	16.5	5.7	1.90	4.03	9.4	42.3
	9	16.3	5.2	1.85	3.89	9.5	40.3
	12	15.9	4.7	1.90	4.48	9.7	38.2

Note: This table reports summary statistics of annualized, at-the-money swaption implied volatilities on the 10-year swap forward yield for four markets (USD, EUR, GBP and JPY). For each combination of market and swaption maturity, the table shows the sample mean (Mean), standard deviation (Stdev), skewness (Skew), kurtosis (Kurt), minimum (Min), and maximum (Max) of implied volatility mid-quotes for maturities ranging from one to twelve months. The number of observations in each series is 189 and runs from April 1996 to December 2011. Data are obtained from Bloomberg and an anonymous broker.

Table 2
Correlation Δ10Y swap rate and Δ implied volatility.

	USD	EUR	JPY	GBP
USD	–	0.59	0.15	0.57
EUR	0.74	–	0.20	0.68
JPY	0.27	0.26	–	0.22
GBP	0.70	0.79	0.19	–

Note: This table reports correlation statistics between the four markets in our sample (USD, EUR, JPY and GBP). Correlations between the monthly changes in the 10 years swap rate are presented below the diagonal. Correlations between the monthly changes in the implied volatility are presented above the diagonal and averaged across the 3, 6, 9 and 12 month swaption maturities. The EUR data before 1999 is from Germany. The number of monthly strategy return observations is 189 and each series runs from April 1996 to December 2011.

4. Empirical results riding the swaption curve

Following the strategy set-up that was discussed in Section 2, we now calculate the empirical returns of the delta–vega and delta–gamma neutral strategies. We report the outcomes for four swaption maturity combinations: short 3-month and long 6-month maturity straddles (3 vs 6), 6 vs 9, 9 vs 12 and 3 vs 12. For each maturity combination we report the return statistics per individual market and for an equally weighted portfolio that comprises all four markets. Table 4 shows the summary statistics, including the average annualized return, standard deviation, *t*-statistic, skewness, kurtosis, Sharpe ratio, first order autocorrelation and the hit ratio.

Most importantly, Table 4 shows consistent positive average returns across all maturities and markets for both delta–gamma and delta–vega neutral strategies. All of the delta–gamma neutral returns have statistically significant means, while 13 out of 16 average returns for the delta–vega neutral strategy are statistically significant. For example, focusing on the 3 vs 6-month delta–gamma neutral strategy average annualized returns are between 0.64% (JPY) and 0.94% (USD), and Sharpe ratios between 0.72 (JPY) and 0.89 (GBP). For the delta–vega neutral strategies returns are slightly wider dispersed with average returns between 0.52% (EUR) and 1.09% (GBP), and Sharpe ratios between 0.54 (USD) and 1.21 (GBP). The Sharpe ratios are comparable to those reported by Cremers et al. (2015) for a similar strategy in the US equity market.[11] In light of our research question, to analyze the term structure of the volatility risk premium, the positive returns are intuitively

[11] Cremers et al. (2015) report a Sharpe ratio of −0.55 for a 1vs2-month delta–gamma neutral strategy and −0.93 for a 1vs2-month delta–vega neutral strategy. Note that these strategies are 'long-short' while our strategies are 'short-long' which explains the opposite sign.

Table 3
Pricing of volatility risk.

	Maturity (m)	Mean (%)	t-stat	Stdev (%)	Skew	Kurt	AC(1) (%)	Sharpe
USD	1	−1.49	−2.60	2.66	0.16	6.68	−13.20	−0.56
	3	−0.43	−0.66	2.14	1.87	8.93	19.80	−0.20
	6	0.53	0.71	2.42	2.51	15.39	22.70	0.22
	9	0.99	1.25	2.62	2.88	19.88	20.30	0.38
	12	1.56	1.82	2.78	2.90	20.57	22.20	0.56
EUR	1	−0.42	−0.87	1.68	−0.05	3.10	6.00	−0.25
	3	0.11	0.24	1.32	1.47	5.01	27.70	0.08
	6	0.73	1.47	1.52	2.12	9.00	20.70	0.48
	9	0.95	1.84	1.65	2.20	9.80	13.90	0.57
	12	1.14	2.09	1.75	2.26	9.99	16.20	0.65
JPY	1	−1.05	−2.53	1.71	0.74	4.08	−7.60	−0.61
	3	−0.82	−2.43	1.25	1.07	2.73	−2.70	−0.66
	6	−0.05	−0.14	1.39	1.16	2.94	−9.10	−0.04
	9	0.22	0.60	1.38	1.08	2.48	−6.30	0.16
	12	0.45	1.24	1.45	0.84	3.22	3.60	0.31
GBP	1	−1.39	−3.24	1.61	0.16	3.64	4.50	−0.86
	3	−0.70	−1.66	1.39	1.17	2.36	25.30	−0.50
	6	0.21	0.46	1.48	1.35	3.07	27.40	0.14
	9	1.23	2.11	1.87	2.18	9.41	29.20	0.66
	12	1.01	1.97	1.60	1.44	3.25	26.70	0.63
EQW	1	−1.09	−3.03	1.35	−0.22	3.69	3.50	−0.81
	3	−0.46	−1.21	1.14	1.32	2.64	33.40	−0.40
	6	0.36	0.81	1.29	1.75	4.75	33.70	0.28
	9	0.85	1.82	1.40	1.78	5.42	32.80	0.61
	12	1.04	2.11	1.43	2.07	7.85	36.80	0.73

Note: This table reports annualized summary statistics of non-overlapping monthly returns on a swaption straddle strategy with daily delta hedging and a one month holding period. The maturities of the underlying swaptions are 1, 3, 6, 9 and 12 months, respectively. We set the notional value of the straddle position equal to one and compute the returns from a long straddle perspective. In addition to the USD, EUR, JPY and GBP markets, we compute the summary statistics of an equally-weighted (EQW) portfolio. Summary statistics include annualized sample mean (Mean), annualized standard deviation (Stdev), skewness (Skew), kurtosis (Kurt), first-order autocorrelation (AC(1)) and annualized Sharpe ratio. *t*-statistics are adjusted according to Newey and West (1987) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

consistent with an upward-sloping term structure in the volatility risk premium. This is consistent with Fornari (2010) and Mueller et al. (2013) who both report negative risk premiums and a downward-sloping term structure of the volatility risk premium (in absolute terms) for the fixed income market.

Next, note that looking across the maturity spectrum, we observe the largest average returns for the shortest maturity combination (3 vs 6-month) and then a decreasing pattern. This pattern is consistent for all markets. For example, the equally weighted portfolio that comprises all four markets earns 0.75% per year on average (*t*-stat of 3.65) with a Sharpe ratio of 1.18 for the 3 vs 6-month delta–gamma neutral portfolio. The returns for the 6 vs 9-month and 9 vs 12-month portfolios are 0.40% (*t*-stat of 3.89) and 0.35% (*t*-stat of 4.25), respectively. Comparable, we see the equally weighted portfolio returns decrease with the maturity for the delta–vega neutral strategy with average annualized returns of 0.81% (*t*-stat of 4.23) for the shortest maturity combination, 0.29% (*t*-stat of 2.50) and 0.23% (*t*-stat of 2.51). Based on this, we conclude that our results suggest that the term structure of the volatility risk premium is concave.

In the spirit of Cremers et al. (2015) we conjecture that the consistent positive strategy returns reported in Table 4 suggest that both volatility risk (delta–gamma) and jump risk (delta–vega neutral) contribute to the term structure in the volatility risk premium. In the remainder of this section we investigate the difference between the delta–gamma and delta–vega neutral strategies in more detail.

In Table 5 we present the pairwise correlations between the delta–gamma and delta–vega neutral strategies for each maturity-market combination. The mean correlation across the four markets is −23.2% for the 3 vs 6-month strategy. This indicates that the two strategies are uncorrelated and probably capture a different effect. The increasing correlations (−3.6% and 37.8%) for longer maturities suggest that both strategies are distinctive but get more in common when maturity increases. The maturity structure in the correlations may be linked to how volatility and jump risk is perceived by investors. Aït-Sahalia et al. (2012) for example find that a jump component is embedded in the volatility risk premium in the US equity market and that "short-term variance risk premia mainly reflect investors' fear of a market crash, rather than the impact of stochastic volatility on the investment opportunity set".

Next, we investigate the link between jump risk and the delta–vega neutral strategy in more detail. The delta–vega strategy has negative gamma exposure. We expect the strategy to make a large negative return when a jump occurs and will analyze the strategy returns during jumps. In Fig. 2 we show the time-series of the daily changes in the 10-year USD swap rate. The vertical lines in Panel A indicate the 1% largest daily changes (absolute) in the daily swap rate. Some of these largest changes could however coincide with periods of high volatility, which might misclassify an observation as a jump. For this reason the vertical lines in Panel B indicate realized jumps according to the non-parametric jump test of Lee and Mykland (2008). If we take out these jump days from our delta–vega strategy returns we expect the returns to be higher. This aligns with our results in Panel B in Table 6. In this table we take out the 1% days with the largest change in the 10-year swap rate from the strategy returns. We do the same for the days with realized jumps according to Lee and Mykland (2008). In both analysis we observe consistent higher returns than the full sample results presented in Table 4. From this finding we infer that there seems to be a link between jump risk and the delta–vega neutral strategy returns. From Panel A in Table 6 we also observe that the returns of the delta–gamma neutral strategy are hardly affected by taking out the jumps.

Finally, we investigate the link between volatility risk and the delta–gamma neutral strategy in more detail. The delta–gamma

Table 4
Summary statistics for long-short straddles trading strategies.

	Maturity	Mean (%)	*t*-stat	Stdev (%)	Skew	Kurt	AC(1) (%)	Sharpe	Hit (%)
Panel A: Delta–gamma neutral combination									
USD	3 vs 6	0.94	2.68	1.20	2.33	14.88	13.99	0.78	55
	6 vs 9	0.62	3.19	0.76	2.38	19.42	−2.71	0.81	62
	9 vs 12	0.47	3.35	0.56	0.33	1.06	−1.65	0.84	56
	3 vs 12	2.57	3.29	2.71	1.86	11.89	9.46	0.95	62
EUR	3 vs 6	0.72	2.99	0.88	2.01	9.06	−3.32	0.81	60
	6 vs 9	0.29	2.54	0.55	0.92	9.35	−20.67	0.53	58
	9 vs 12	0.34	2.92	0.49	1.23	5.74	−4.14	0.69	61
	3 vs 12	1.72	3.41	2.07	2.50	14.66	−11.06	0.83	61
JPY	3 vs 6	0.64	2.72	0.89	1.71	8.90	−6.79	0.72	59
	6 vs 9	0.32	2.13	0.55	0.82	3.64	−1.68	0.59	51
	9 vs 12	0.35	2.53	0.56	−0.01	2.46	−7.32	0.62	59
	3 vs 12	1.66	3.1	2.06	1.34	6.77	−8.70	0.81	62
GBP	3 vs 6	0.69	2.97	0.78	0.88	1.51	13.10	0.89	56
	6 vs 9	0.37	2.53	0.55	0.00	1.52	1.40	0.68	57
	9 vs 12	0.23	1.71	0.50	−0.40	3.52	−2.49	0.45	55
	3 vs 12	1.60	3.02	1.72	0.95	1.78	15.78	0.93	58
EQW	3 vs 6	0.75	3.65	0.63	1.36	3.26	19.31	1.18	59
	6 vs 9	0.40	3.89	0.37	1.34	5.51	4.64	1.10	63
	9 vs 12	0.35	4.25	0.29	0.28	1.88	10.98	1.17	66
	3 vs 12	1.89	4.33	1.40	1.65	5.37	16.42	1.35	63
Panel B: Delta–vega neutral combination									
USD	3 vs 6	0.85	2.51	1.57	−2.73	12.81	−6.74	0.54	70
	6 vs 9	0.36	1.84	0.91	−3.05	16.74	−1.52	0.40	67
	9 vs 12	0.26	1.76	0.67	−1.27	5.65	0.62	0.39	62
	3 vs 12	1.25	2.34	2.47	−2.87	14.05	−3.68	0.51	69
EUR	3 vs 6	0.52	2.17	0.90	−1.48	5.63	3.83	0.58	65
	6 vs 9	0.11	0.73	0.54	−1.61	6.32	8.51	0.20	64
	9 vs 12	0.14	1.27	0.45	−0.13	6.44	3.24	0.32	59
	3 vs 12	0.68	1.78	1.39	−1.76	7.11	7.59	0.48	64
JPY	3 vs 6	0.79	3.17	1.06	−2.65	12.60	−8.50	0.75	74
	6 vs 9	0.23	1.29	0.74	−2.48	16.14	−7.03	0.31	64
	9 vs 12	0.29	2.09	0.50	−1.15	6.30	5.57	0.58	65
	3 vs 12	1.10	2.71	1.68	−2.96	16.02	−5.87	0.65	71
GBP	3 vs 6	1.09	5.05	0.90	−2.46	12.00	−0.63	1.21	74
	6 vs 9	0.44	3.50	0.55	−0.77	2.22	−3.28	0.80	67
	9 vs 12	0.21	1.65	0.45	−0.11	2.30	7.04	0.47	59
	3 vs 12	1.52	4.46	1.34	−2.08	9.37	4.90	1.13	72
EQW	3 vs 6	0.81	4.23	0.76	−2.01	8.32	6.00	1.07	68
	6 vs 9	0.29	2.50	0.44	−1.76	6.44	10.78	0.66	64
	9 vs 12	0.23	2.51	0.34	−0.91	2.89	6.31	0.66	61
	3 vs 12	1.14	3.69	1.19	−1.99	7.72	8.94	0.95	67

Note: This table reports annualized summary statistics of non-overlapping monthly returns on long-short swaption straddles strategies. Each month a swaption straddle with the lowest maturity is sold with a notional of one, and held for one month. At the same time an additional long straddle position, with a higher maturity, is bought at a notional that either neutralizes the vega or gamma exposure of the combined long-short position. The straddles are initiated on the last business day of the month. In addition to the USD, EUR, JPY and GBP markets, we compute the summary statistics of an equally-weighted (EQW) portfolio. Summary statistics include annualized sample mean (Mean), annualized standard deviation (Stdev), skewness (Skew), kurtosis (Kurt), first-order autocorrelation (AC(1)), annualized Sharpe ratio and the percentage of months with a positive return (Hit). *t*-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

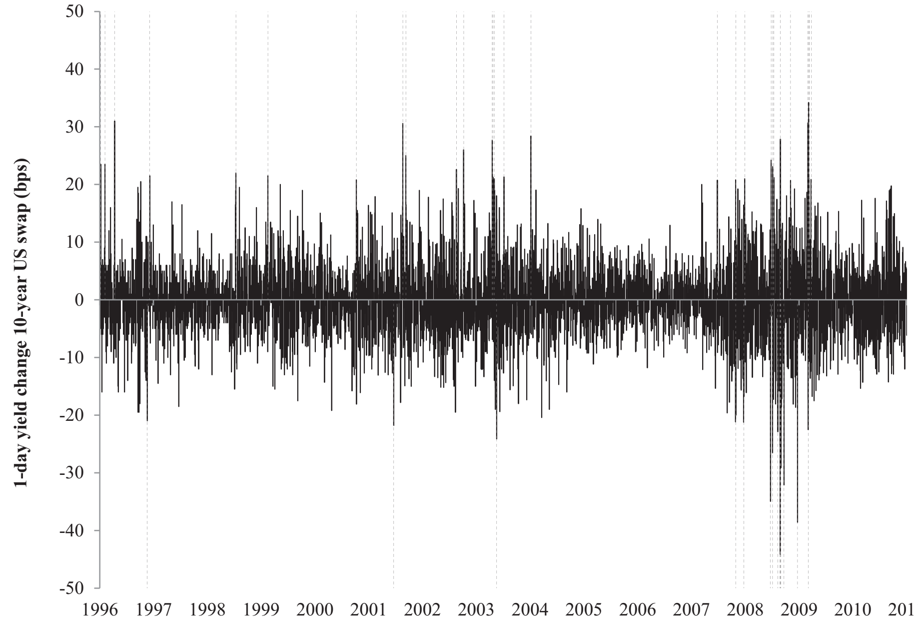
Table 5
Pairwise correlations.

	3 vs 6 (%)	6 vs 9 (%)	9 vs 12 (%)	3 vs 12 (%)
USD	−38.4	−30.0	30.7	−34.7
EUR	−19.5	−8.2	28.2	−32.0
JPY	−31.1	0.6	40.3	−33.7
GBP	−3.8	23.3	51.8	−21.4
Average	−23.2	−3.6	37.8	−30.5

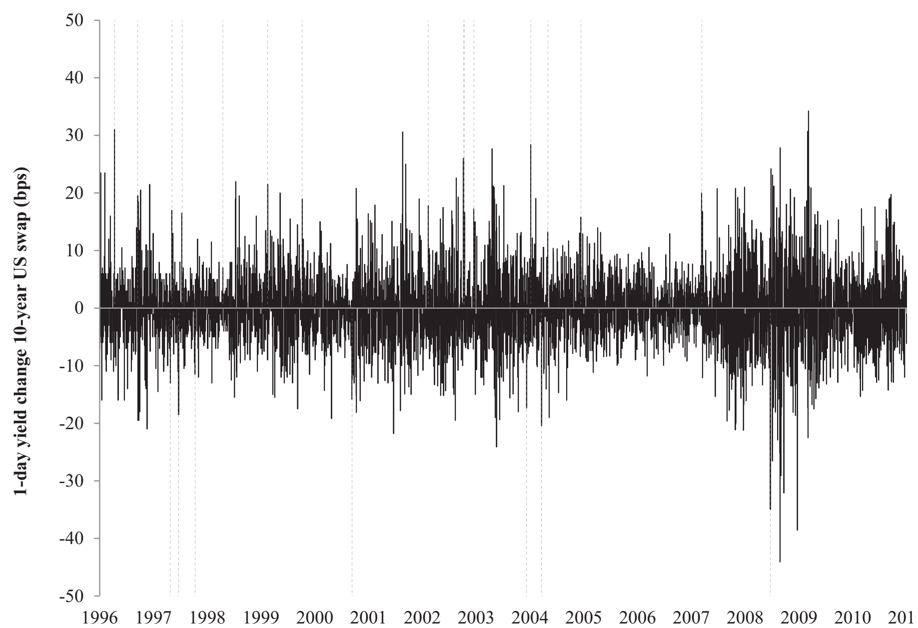
Note: This table reports pairwise correlations between the delta–gamma and delta–vega neutral strategy returns. Correlations are computed separately for the combinations of market and swaption maturities. The number of monthly strategy return observations is 189 and each series runs from April 1996 to December 2011.

strategy has positive vega exposure and is constructed such that it makes a positive return if the market expectation of future volatility rises. For this reason we expect the delta–gamma strategy returns to be lower if we take out the months with the largest increase in volatility. This is what we find in Panel A in Table 6 where we take out the strategy return for the 5% months with the largest increase in realized volatility. We note that all maturity combinations have mean returns lower than the full sample results presented in Table 4. For example, the average return for the 3 vs 6-month USD delta–gamma neutral strategy decreases from 0.94% to 0.47%. This result suggests that there might be a link between the delta–gamma strategy returns and the volatility risk premium. From Panel B in Table 6 we also observe that the returns of the delta–gamma neutral strategy are positively affected by taking out the 5% months with the largest increase in realized volatility. It may be the case that these months (partly) overlap with jumps in the underlying swap rate.

The evidence presented in this section, which essentially shows that long-short swaption straddles strategies produce positive



(a) Realized jumps defined as 1% largest absolute changes



(b) Realized jumps according to Lee and Mykland (2008)

Fig. 2. Time series of daily swap rate changes and realized jumps. This figure illustrates the difference between detection methods for jumps in the times series of daily changes of the 10 years swap rate for the USD market. The vertical, dashed lines in Panel A represent realized jumps defined as the 1% largest absolute changes in the daily swap rate (41 observations). The vertical, dashed lines in Panel B represent realized jumps (22 observations) according to Lee and Mykland (2008). The sample runs from April 1996 to December 2011 and includes 4110 daily observations.

average returns that decrease in maturity, is consistent with a concave, upward-sloping term structure in the volatility risk premium. The fact that both delta–vega and delta–gamma neutral strategies earn positive returns that seem uncorrelated suggests that the term structure of the volatility risk premium is affected by both jump risk and volatility risk. This finding contributes to recent studies on the pricing of jump and volatility risk in the fixed income market such as Trolle and Schwartz (2014) and Li and Song (2013).

5. Robustness and sensitivity analysis

In this section we present a variety of additional sensitivity and robustness analysis of our main findings. We first test the delta-neutrality of our strategy and analyze the empirical relationship between the strategy returns and rate changes. Moreover, we investigate the impact of macroeconomic releases. Next, we check if our main results can be confirmed using the Vasicek (1977) model and a stochastic volatility

Table 6
Effect of jumps on strategy returns.

		Excl. Jumps (1%)			Excl. Jumps (LM2008)			Excl. ΔVol (5%)		
		Mean (%)	*t*-stat	Sharpe	Mean (%)	*t*-stat	Sharpe	Mean (%)	*t*-stat	Sharpe
Panel A: Delta–gamma neutral combination										
USD	3 vs 6	0.84	2.54	0.76	0.90	2.51	0.77	0.47	1.74	0.50
	6 vs 9	0.52	2.86	0.74	0.59	3.29	0.79	0.36	2.29	0.61
	9 vs 12	0.43	3.13	0.75	0.43	3.13	0.76	0.37	2.80	0.68
	3 vs 12	2.27	3.31	0.97	2.42	3.23	0.94	1.56	2.50	0.72
EUR	3 vs 6	0.54	2.83	0.70	0.71	3.02	0.81	0.30	1.66	0.46
	6 vs 9	0.27	2.62	0.53	0.29	2.50	0.52	0.07	0.79	0.17
	9 vs 12	0.30	2.57	0.61	0.35	2.89	0.71	0.22	2.06	0.51
	3 vs 12	1.44	3.38	0.79	1.73	3.42	0.84	0.80	2.07	0.53
JPY	3 vs 6	0.34	1.85	0.44	0.56	2.42	0.65	0.28	1.47	0.40
	6 vs 9	0.21	1.86	0.39	0.26	1.65	0.48	0.17	1.28	0.34
	9 vs 12	0.37	2.36	0.53	0.89	1.50	0.38	0.28	2.04	0.52
	3 vs 12	1.26	2.86	0.63	2.47	2.00	0.50	0.95	2.22	0.56
GBP	3 vs 6	0.65	3.03	0.83	0.68	2.94	0.85	0.33	1.87	0.51
	6 vs 9	0.26	1.74	0.48	0.38	2.61	0.70	0.23	1.70	0.44
	9 vs 12	0.28	1.91	0.53	0.22	1.65	0.43	0.11	0.89	0.22
	3 vs 12	1.50	2.93	0.86	1.59	3.02	0.91	0.84	2.11	0.58
EQW	3 vs 6	0.59	3.51	1.04	0.71	3.49	1.13	0.33	1.46	0.77
	6 vs 9	0.31	3.38	0.90	0.38	3.89	1.07	0.19	1.80	0.75
	9 vs 12	0.34	4.27	1.09	0.47	2.77	0.73	0.23	3.10	0.91
	3 vs 12	1.62	4.34	1.26	2.05	3.96	1.16	0.98	2.48	1.06
Panel B: Delta–Vega neutral combination										
USD	3 vs 6	1.43	4.29	1.13	1.05	3.24	0.70	1.32	3.80	0.97
	6 vs 9	0.64	4.19	0.87	0.45	2.27	0.52	0.68	4.00	0.90
	9 vs 12	0.42	3.05	0.67	0.30	2.08	0.46	0.46	2.96	0.75
	3 vs 12	2.11	4.56	1.10	1.53	3.01	0.66	2.05	3.86	0.97
EUR	3 vs 6	0.76	3.28	0.91	0.60	2.56	0.70	0.65	2.78	0.79
	6 vs 9	0.30	2.38	0.61	0.15	1.00	0.28	0.23	1.61	0.47
	9 vs 12	0.24	2.39	0.56	0.17	1.59	0.38	0.27	2.48	0.65
	3 vs 12	1.10	3.17	0.87	0.79	2.16	0.60	0.96	2.62	0.76
JPY	3 vs 6	1.11	5.53	1.45	0.83	3.37	0.82	1.09	5.27	1.25
	6 vs 9	0.48	3.75	0.90	0.25	1.48	0.35	0.47	2.82	0.78
	9 vs 12	0.49	3.61	0.86	0.79	1.62	0.40	0.46	4.31	1.08
	3 vs 12	1.70	5.50	1.41	1.43	3.53	0.78	1.66	5.04	1.24
GBP	3 vs 6	1.31	6.21	1.60	1.18	5.62	1.43	1.36	6.59	1.87
	6 vs 9	0.49	4.28	0.93	0.49	3.99	0.94	0.64	5.58	1.33
	9 vs 12	0.35	2.51	0.75	0.23	1.85	0.51	0.33	2.71	0.79
	3 vs 12	1.85	5.66	1.50	1.65	4.99	1.34	1.99	6.36	1.83
EQW	3 vs 6	1.15	6.48	1.81	0.91	5.06	1.29	1.05	5.92	1.71
	6 vs 9	0.48	5.66	1.26	0.34	3.08	0.81	0.48	5.15	1.41
	9 vs 12	0.38	4.73	1.17	0.38	2.72	0.63	0.36	5.62	1.25
	3 vs 12	1.69	6.46	1.71	1.35	4.86	1.17	1.57	5.97	1.67

Note: This table reports annualized summary statistics of non-overlapping monthly returns on long-short swaption straddles strategies for three differently truncated samples. First, we take out the days on which the absolute daily change in the 10-year swap rate belongs to the 1% largest changes in our sample period (excl. Jumps (1%)). Secondly, we take out the days on which the 10-year swap rate jumped (excl. Jumps (LM2008)) according to Lee and Mykland (2008). Thirdly, we take out the 5% months with the largest increase in realized volatility (excl. ΔVol (5%)). The realized volatility is calculated as the standard deviation of daily changes of 10 years swap rate during the month. Summary statistics include annualized sample mean (Mean), *t*-statistics (*t*-stat) and annualized Sharpe ratio (Sharpe). *t*-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The samples run from April 1996 to December 2011.

model. Finally, we re-run our strategies on two additional data sets which include the 2-year tenor and swaption smile data for the USD.

5.1. Hedging efficiency

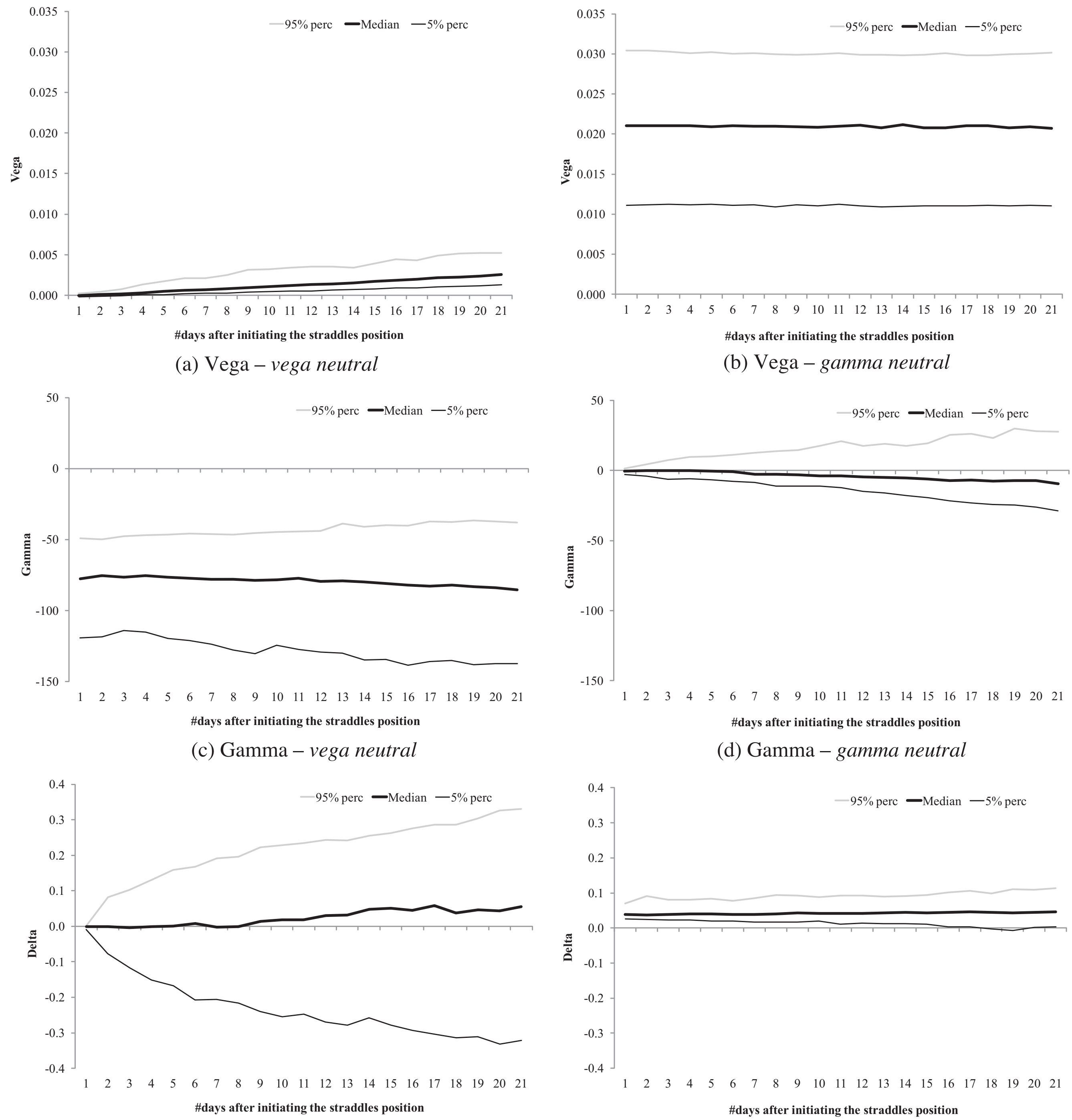
A potential concern might be that our straddles are not delta neutral but exposed to changes in the underlying swap rate. This exposure could originate from at least two channels: monthly rebalancing instead of daily rebalancing and a violation of the assumptions of the Black model in our data set. To examine the impact of monthly rebalancing, we graphically analyze the daily intra-month Black risk exposures for the 3- vs 6-month strategies. Next, to investigate the exposure to the underlying empirically, we regress the strategy returns on the rate changes. The specification of this model is:

$$RLS_t = \beta_0 + \beta_1 \Delta SR_t^{10Y} + \varepsilon_t \tag{12}$$

where RLS_t is the return of the long-short straddles strategy in month t and ΔSR_t^{10Y} is the difference between the 10-year swap rate in month t and $t-1$.

Most likely, risk exposures will change during the month because of the changes in the underlying and in the implied volatility. This could potentially impact the strategy returns and bias our conclusions. To address this discretization error, as highlighted by Branger and Schlag (2008), Fig. 3 plots the average daily risk exposures for the USD 3 vs 6-month strategies and illustrates how the Black delta, gamma and vega develop between two monthly rebalances.[12] Each panel plots a single risk exposure and shows the 5%

[12] The results for the other maturities and markets are similar and available upon request.



(a) Vega – *vega neutral*
(b) Vega – *gamma neutral*
(c) Gamma – *vega neutral*
(d) Gamma – *gamma neutral*
(e) Delta – *vega neutral*
(f) Delta – *gamma neutral*

Fig. 3. Strategy risk exposures ("Greeks") during the month. This figure plots the average (over time series) risk exposures ('Greeks') of the delta–gamma and delta–vega neutral 3 vs 6 month calendar spread straddles strategy in the USD market. For each working day of the month, the Greeks are calculated using the Black model. Delta is the sensitivity of the straddle to the underlying swap forward rate, vega is the sensitivity to the implied volatility and gamma is the sensitivity of the delta to the underlying swap forward rate.

percentile, median and 95% percentile across all months in our data sample. Most importantly, we note that the median delta exposures for both the delta–vega hedge (Panel E) and the delta–vega hedge (Panel F) stay very close to zero and are 0.04 and 0.06 respectively after one month. Notwithstanding, the 90% bandwidth for the delta–gamma neutral strategy is smaller than for the delta–vega neutral strategy. Based on this observation, we conclude that it seems unlikely that the outcomes are the result of a large exposure to the underlying.

Continuing on the exposure to the underlying, Table 7 reports the results from estimating Eq. (12) and shows some interesting features. For the delta–gamma-neutral strategy we observe negative estimates for β_1, that are statistically significant for the USD, EUR and GBP markets. The coefficients for JPY are not statistically significant. This being said, 15 out of 16 estimates for β_0 are statistically significant, indicating that the strategy returns do not appear to be explained by exposure to the underlying swap rate. These results contrast with the results for the delta–vega neutral strategy. Here we see only two positive estimates for β_1, that are statistically significant; all other coefficients are not statistically significant. The strategy returns after correcting for the change in the swap rate remain statistically significant for 13 out of 16 strategies and are very close to the unadjusted returns reported in Table 4.

Finally, we expand the model in Eq. (12) with three additional factors; the monthly change of the slope of the yield curve ($\Delta 10Y3M_t$), the monthly change of the implied volatility ($\Delta\sigma_t$), and the delta-hedged return of a 1-month short straddle position ($R_t^{straddle}$). We define the slope of the yield curve as the difference between the 3-month rate and the 10-year swap rate. That is, the model is given by

$$RLS_t = \beta_0 + \beta_1 \Delta SR_t^{10Y} + \beta_2 \Delta 10Y3M_t + \beta_3 \Delta\sigma_t + \beta_4 R_t^{straddle} + \varepsilon_t \quad (13)$$

The four factor model is estimated and the estimation results are reported in Table 8. Most importantly, we observe that 15 out of 16 and 11 out of 16 estimates for the intercept, β_0, are statistically significant at a 10% level for the delta–gamma neutral and delta–vega neutral strategies respectively. This suggests that the strategy returns do not appear to be explained by the four factors. Additionally, we see negative sensitivities for the change in volatility and positive sensitivities for the 1-month straddle returns for the delta–vega neutral strategy. Furthermore, the returns for the delta–gamma neutral strategy are positively correlated with the change in the implied volatility, as evidenced by the positive and significant estimates of β_3. Finally, the estimates for the coefficients of the change of the 10-year yield and the slope are insignificant for the majority of maturity-market combinations.

We close this section by concluding that the evidence presented in this section suggest that it seems unlikely that the strategy returns can fully be explained by exposures to the underlying swap rate, the slope of the yield curve, the implied volatility or 1-month delta-hedged returns.

5.2. Day of the month

Several studies have documented that bond markets respond to scheduled macroeconomic announcements, even more strongly than the stock markets (see e.g. Andersen et al. (2007)). In this section we consider a possible day-of-the-month effect because the majority of these macroeconomic measures is released around the turn of the month. Since the scheduled macroeconomic announcements impact bond yields but also the volatility risk (Fornari, 2010) and jump risk (Li and Song, 2013) premia, these announcements might also influence the returns of the delta–vega and delta–gamma neutral strategies. Announcements might have a larger impact on the long-short returns when the position is not delta, gamma or vega neutral. Therefore, the specific day of the month that we have chosen to open and close our positions may impact our earlier results. Until now, we used the data of the last trading day of the month to open new straddle positions and to close the previous straddle positions. To assess whether our earlier results are impacted by macroeconomic announcements we initiate the monthly straddle combinations for each individual working day of the month. For example, we open the long-short straddles position on the first day of the month instead of the last day, etc.

In Fig. 4 we plot the average strategy returns across different inception days of the month. For the delta–gamma neutral strategy (Panel A) we observe almost no differences between the average returns across different days of the month. In contrast, we see a small day-of-the-month effect in the returns for the delta–vega neutral strategy (Panel B). Average returns are somewhat higher around month end and lower in the middle of the month, but all returns are statistically significant. Further analysis (not shown) indicates that volatilities of the returns are stable over the month implying that the differences between returns are not caused by a higher risk. As Dungey et al. (2009) relates jumps to the release of macroeconomic data in the fixed income market, the day-of-the-month results seem to confirm the link between the delta–vega hedged results and jump risk. Overall, the day-of-the-month analysis which essentially shows statistically significant and positive returns for all days of the month, indicates that our results are not driven by a specific choice of the inception day.

5.3. Beyond Black's model

To address the concern that the assumptions behind the Black model can be violated in practice and might affect the effectiveness of our hedges, we analyze the robustness of our main findings by re-running our strategies on the Vasicek (1977) model and the SABR model.

5.3.1. Vasicek model

The assumptions behind the Vasicek model are almost equal to the Black model. The only difference is that the Vasicek model assumes a constant absolute volatility (normal distribution) while the Black model assumes a constant relative volatility (lognormal distribution).[13] The consequence is that the gamma of a straddle in the Vasicek model differs from the gamma of the Black model:

$$\Gamma_{Vasicek} = \frac{\partial S^2}{\partial F^2} = \frac{LA}{m\sigma_{abs}\sqrt{T}}[N'(d_1) + N'(-d_1)] \quad (14)$$

where σ_{abs} is the absolute volatility that is equal to σF. Numerically the delta–gamma neutral hedge on basis of the Vasicek model is exactly the same as the delta–gamma neutral hedge on basis of Black's gamma (see Section 2.3). The delta–vega neutral hedge ratio is different though. The vega risk parameter on basis of the Vasicek model is equal to:

$$\upsilon_{Vasicek} = \frac{\partial S}{\partial \sigma_{abs}} = \frac{LA\sqrt{T}}{m}[N'(d_1) + N'(-d_1)] \quad (15)$$

To obtain a delta–vega neutral hedge we can now derive that the hedge ratio on basis of the Vasicek model should be equal to $\frac{\sqrt{T}}{\sqrt{T_{hedge}}}$.

Table 9 shows the return statistics for the delta–vega neutral strategies. For all markets we find comparable statistics to our main findings reported in Table 4. This suggests that our findings are robust for assuming a constant absolute volatility.

5.3.2. SABR model

This section considers a stochastic volatility model as alternative to the deterministic volatility models that we have used so far. We select the SABR model, introduced in Hagan et al. (2002), because it is widely used in the market (Rebonato et al., 2009).

The SABR model allows for a relation between the implied volatility (σ) and the underlying swap forward rate F. For this reason the delta in the SABR model (Δ_{SABR}) differs from the delta in the Black model. We use the (Bartlett, 2006) modified SABR delta.

[13] In the Vasicek model the volatility is measured as an absolute value and not relative to the underlying swap forward as in the Black model. For example, a volatility of 50% for a swap rate of 2% implies an absolute volatility of 100 bp. The same absolute volatility of 100 bp leads to a relative volatility of 20% for a swap rate of 5%.

Table 7
Regression of strategy returns on swap rate changes.

		Gamma neutral					Vega neutral				
		β_0 (%)	*t*-stat	β_1	*t*-stat	R^2	β_0 (%)	*t*-stat	β_1	Coef	R^2
USD	3 vs 6	0.83	2.71	−0.35	−1.74	0.09	0.88	2.52	0.09	0.27	0.00
	6 vs 9	0.51	3.38	−0.36	−3.31	0.22	0.36	1.87	0.00	−0.01	0.00
	9 vs 12	0.43	3.14	−0.15	−2.75	0.07	0.28	1.76	0.04	0.30	0.00
	3 vs 12	2.23	3.35	−1.12	−2.89	0.17	1.28	2.35	0.11	0.20	0.00
EUR	3 vs 6	0.57	2.72	−0.52	−2.92	0.14	0.60	2.48	0.28	1.46	0.04
	6 vs 9	0.19	2.05	−0.37	−3.68	0.18	0.15	0.99	0.14	1.20	0.03
	9 vs 12	0.25	2.41	−0.31	−4.00	0.16	0.16	1.46	0.09	1.02	0.01
	3 vs 12	1.29	3.16	−1.58	−3.59	0.23	0.79	2.08	0.43	1.37	0.04
JPY	3 vs 6	0.68	2.73	0.29	1.04	0.03	0.72	2.77	−0.44	−1.15	0.05
	6 vs 9	0.32	2.06	0.01	0.08	0.00	0.17	0.94	−0.38	−1.35	0.07
	9 vs 12	0.34	2.35	−0.03	−0.21	0.00	0.26	1.74	−0.17	−1.07	0.03
	3 vs 12	1.70	2.95	0.25	0.40	0.00	0.98	2.29	−0.79	−1.23	0.06
GBP	3 vs 6	0.62	2.93	−0.20	−1.93	0.03	1.23	5.95	0.37	1.84	0.08
	6 vs 9	0.30	2.28	−0.19	−2.86	0.06	0.50	4.26	0.15	1.52	0.04
	9 vs 12	0.17	1.35	−0.13	−2.31	0.04	0.25	2.14	0.10	1.51	0.02
	3 vs 12	1.34	2.86	−0.67	−2.94	0.08	1.72	5.52	0.53	1.79	0.08

Note: This table presents estimated results for the contemporaneous regression of the monthly strategy returns on the monthly change of the 10-year swap rate.
$RLS_t = \beta_0 + \beta_1 \Delta SR_t^{10Y} + \varepsilon_t$,
where RLS_t is the return of the long-short straddles strategy in month t and ΔSR_t is the difference of the 10-year swap rate (SR_t^{10Y}) in month t and $t-1$. For each market and long-short maturity combination we estimate the model separately. t-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

Table 8
Regression of strategy returns on swap rate, yield curve steepness and relative volatility changes and the daily delta-hedged straddle return.

		β_0 (%)	*t*-stat	β_1	*t*-stat	β_2	*t*-stat	β_3	*t*-stat	β_4	*t*-stat	R^2
Panel A: Delta–gamma neutral combination												
USD	3 vs 6	0.80	3.36	−0.11	−1.06	0.16	2.17	0.06	5.54	−0.01	−0.31	0.55
	6 vs 9	0.51	3.99	−0.15	−2.64	0.04	0.82	0.04	6.38	−0.01	−0.61	0.53
	9 vs 12	0.39	2.90	−0.09	−1.64	0.03	0.86	0.02	2.54	0.01	0.78	0.12
	3 vs 12	1.99	3.97	0.06	0.28	0.32	1.96	0.29	8.85	0.03	0.56	0.69
EUR	3 vs 6	0.54	3.52	−0.11	−1.07	0.10	1.49	0.08	10.72	0.04	1.46	0.65
	6 vs 9	0.17	2.28	−0.09	−1.65	−0.01	−0.25	0.05	9.06	0.01	0.74	0.51
	9 vs 12	0.23	2.36	−0.15	−2.26	0.01	0.39	0.03	4.91	0.03	1.13	0.31
	3 vs 12	1.14	4.48	0.02	0.12	0.04	0.33	0.32	8.64	0.08	1.26	0.83
JPY	3 vs 6	0.54	2.76	0.01	0.03	0.22	1.23	0.04	8.22	0.08	2.02	0.52
	6 vs 9	0.32	2.46	−0.27	−1.04	0.35	1.32	0.02	4.23	−0.02	−0.62	0.24
	9 vs 12	0.33	2.11	0.19	0.86	−0.14	−0.65	0.02	4.08	0.01	0.23	0.12
	3 vs 12	1.59	3.13	0.78	1.29	0.59	1.10	0.14	6.43	0.01	0.17	0.55
GBP	3 vs 6	0.52	3.52	0.03	0.32	0.12	1.37	0.08	9.36	0.04	1.40	0.56
	6 vs 9	0.24	2.34	−0.07	−1.13	0.06	1.27	0.04	4.70	0.03	1.18	0.26
	9 vs 12	0.19	1.55	−0.12	−1.70	0.09	2.30	0.02	1.94	−0.02	−1.15	0.11
	3 vs 12	1.11	4.04	0.19	0.85	0.16	0.92	0.32	13.48	0.10	1.85	0.74
Panel B: Delta–vega neutral combination												
USD	3 vs 6	0.72	2.44	−0.21	−0.85	−0.12	−1.04	−0.06	−3.69	0.12	2.90	0.35
	6 vs 9	0.32	2.15	−0.21	−1.56	−0.14	−2.11	−0.05	−5.19	0.06	3.08	0.46
	9 vs 12	0.23	1.77	−0.18	−1.90	−0.04	−1.29	−0.04	−6.94	0.04	2.41	0.37
	3 vs 12	0.96	2.04	−0.41	−1.11	−0.32	−1.78	−0.13	−3.57	0.28	5.61	0.32
EUR	3 vs 6	0.51	2.80	0.04	0.28	−0.02	−0.16	−0.03	−2.01	0.20	3.28	0.32
	6 vs 9	0.11	0.99	−0.02	−0.19	−0.08	−1.41	−0.03	−3.68	0.11	3.15	0.37
	9 vs 12	0.14	1.54	−0.11	−2.03	−0.02	−0.55	−0.03	−5.66	0.07	5.83	0.35
	3 vs 12	0.64	2.23	0.07	0.28	−0.12	−0.81	−0.07	−1.97	0.36	5.45	0.32
JPY	3 vs 6	0.56	2.54	−0.33	−0.75	−0.09	−0.28	−0.02	−2.16	0.19	2.64	0.35
	6 vs 9	0.09	0.57	−0.49	−1.36	0.07	0.27	−0.02	−2.43	0.09	2.29	0.39
	9 vs 12	0.20	1.45	−0.01	−0.04	−0.25	−1.40	−0.01	−1.66	0.06	3.33	0.20
	3 vs 12	0.57	1.46	−0.72	−0.90	−0.31	−0.59	−0.03	−1.36	0.40	4.42	0.30
GBP	3 vs 6	0.89	4.52	0.30	1.54	−0.11	−0.76	−0.02	−1.38	0.24	5.26	0.34
	6 vs 9	0.34	3.49	0.02	0.30	−0.03	−0.62	−0.03	−3.92	0.11	5.85	0.37
	9 vs 12	0.20	1.97	−0.05	−0.97	0.01	0.13	−0.04	−6.14	0.04	2.49	0.32
	3 vs 12	1.18	4.33	0.34	1.28	−0.14	−0.72	−0.05	−2.32	0.38	7.66	0.39

Note: This table presents estimated results for the following contemporaneous regression model.
$RLS_t = \beta_0 + \beta_1 \Delta SR_t^{10Y} + \beta_2 \Delta 10Y3M_t + \beta_3 \Delta\sigma_t + \beta_4 R_t^{straddle} + \varepsilon_t$,
where RLS_t is the return of the long-short straddles strategy in month t, ΔSR_t^{10Y} is the difference of the 10-year swap rate (SR^{10Y}) in month t and $t-1$, $\Delta\sigma_t$ is the difference of the relative implied volatility (σ) in month t and $t-1$ and $R_t^{straddle}$ is the daily delta-hedged return on a delta neutral straddle in month t. For each market and long-short maturity combination we estimate the model separately. t-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

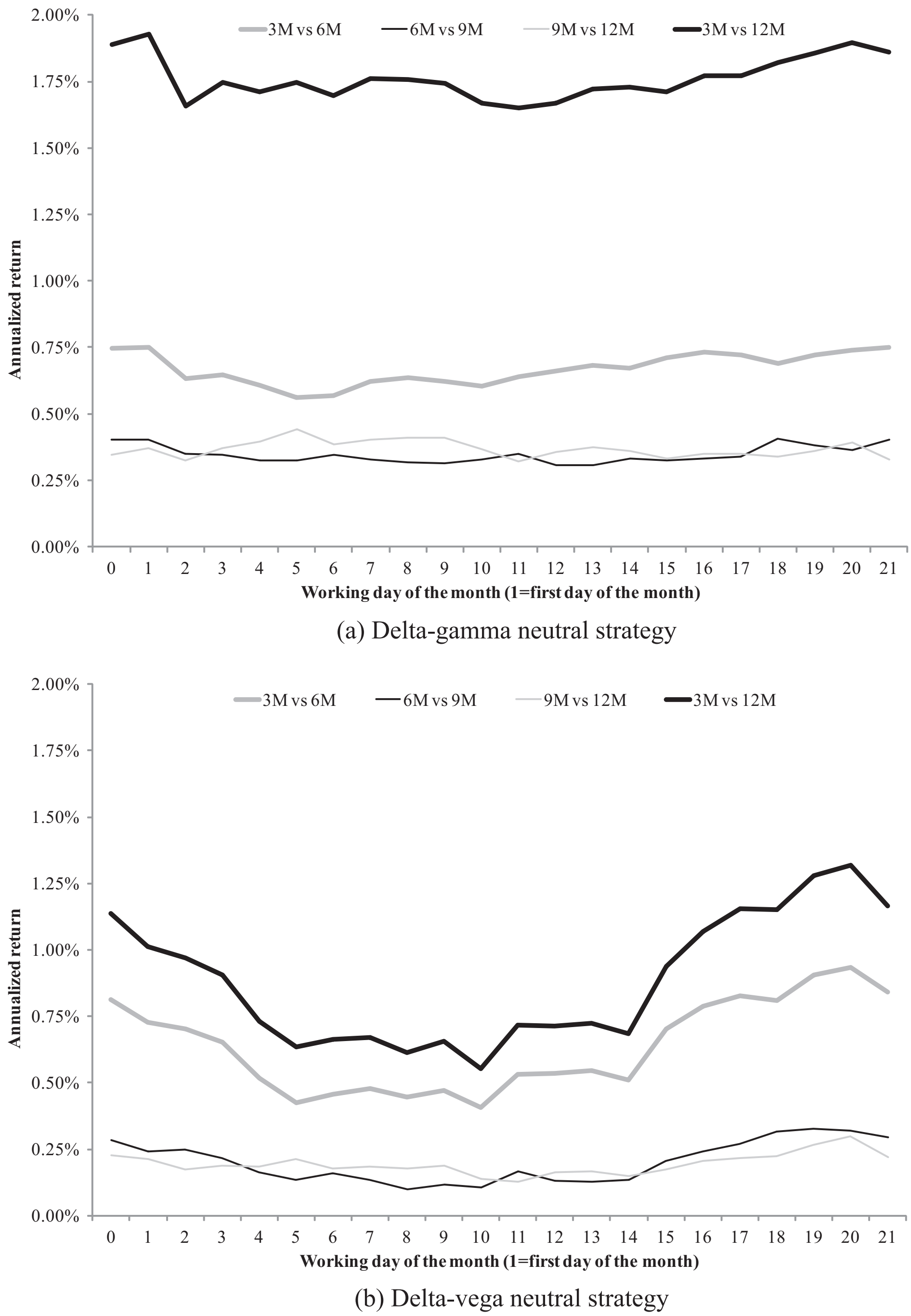


Fig. 4. Day-of-the-month return effect. This figure shows the portfolio returns of the long-short straddles strategies across inception days at different working days of the month. Portfolio returns are the equally weighted (EQW) average returns for the USD, EUR, GBP and JPY markets. The number of observations in each series is 189 and runs from April 1996 to December 2011. $t = 0$ is the last working day of the previous month.

$$\Delta_{SABR} = \Delta + v\left[\frac{\partial\sigma}{\partial F} + \frac{\partial\sigma}{\partial\alpha}\frac{\rho v}{F^{\beta}}\right] \tag{16}$$

where Δ and v on the right hand side are the original Black delta (7) and Black vega (9) respectively.

According to the SABR model, the at-the-money straddle position is not necessarily delta neutral. Therefore, we analyze a SABR delta neutral strategy using a long-short combination of two straddles, instead of a delta–gamma neutral strategy. Likewise, we also analyze a SABR vega neutral strategy using the adjusted vega formula from Bartlett (2006) with the caveat that the vega hedge on basis of the SABR model is not necessarily delta neutral under the SABR model.

$$v_{SABR} = v\left[\frac{\partial\sigma}{\partial\alpha} + \frac{\partial\sigma}{\partial F}\frac{\rho F^{\beta}}{v}\right] \tag{17}$$

Similarly to our main analysis, we take a short position of one straddle contract in the shorter-term maturity and a long position in the longer-term maturity with a hedge ratio that either neutralizes the estimated SABR delta or SABR vega. For the empirical analysis we have gathered swaption smile data for USD swaptions from JP Morgan because we need smile data to estimate the SABR model.

Table 9
Summary statistics for trading strategies on the Vasicek model.

		Vega neutral			
		Mean (%)	*t*-stat	Stdev (%)	Sharpe
USD	3 vs 6	0.86	2.60	1.53	0.56
	6 vs 9	0.38	2.10	0.85	0.45
	9 vs 12	0.25	1.70	0.68	0.37
	3 vs 12	1.28	2.44	2.41	0.53
EUR	3 vs 6	0.52	2.21	0.88	0.59
	6 vs 9	0.11	0.79	0.52	0.22
	9 vs 12	0.15	1.40	0.43	0.35
	3 vs 12	0.69	1.85	1.36	0.51
JPY	3 vs 6	0.78	3.32	1.01	0.78
	6 vs 9	0.23	1.41	0.69	0.34
	9 vs 12	0.27	2.04	0.48	0.56
	3 vs 12	1.10	2.84	1.61	0.68
GBP	3 vs 6	1.09	5.06	0.90	1.21
	6 vs 9	0.44	3.57	0.54	0.82
	9 vs 12	0.22	1.76	0.44	0.50
	3 vs 12	1.52	4.54	1.32	1.16
EQW	3 vs 6	0.81	4.34	0.74	1.09
	6 vs 9	0.29	2.73	0.41	0.71
	9 vs 12	0.22	2.53	0.33	0.67
	3 vs 12	1.15	3.82	1.16	0.99

Note: This table reports annualized summary statistics of non-overlapping monthly returns on long-short swaption straddles strategies. Each month a swaption straddle with the lowest maturity is sold with a notional of one, and held for one month. At the same time an additional long straddle position, with a higher maturity, is bought at a notional that neutralizes the vega exposure of the combined long-short position according to the Vasicek (1977) model. The straddles are initiated on the last business day of the month. In addition to the USD, EUR, JPY and GBP markets, we compute the summary statistics of an equally-weighted (EQW) portfolio. Summary statistics include annualized sample mean (Mean), annualized standard deviation (Stdev), skewness (Skew), kurtosis (Kurt), first-order autocorrelation (AC(1)), annualized Sharpe ratio and the percentage of months with a positive return (Hit). *t*-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

We estimate the parameters of the SABR model with a fixed beta parameter of 0.5, which seems to be market practice in the US according to Rebonato et al. (2009).

Table 10 tabulates the summary statistics for the delta neutral and vega neutral long-short strategies using the SABR model for hedging. The average returns are positive across all maturities for both delta and vega neutral strategies. Both strategies have statistically significant means for 3 vs 6 and 6 vs 9-month maturity combinations at a 90% confidence level. In general, the vega neutral returns and Sharpe ratios under the SABR model seem comparable to the returns and Sharpe ratios under the Black model. For example the 3 vs 6-month strategy has a return (Sharpe ratio) of 0.89% (0.60) under the SABR model and 0.85% (0.54) under the Black model. Based on these results we conclude that our main findings are robust.

5.4. Swaption smile and 2-year tenor

As a final robustness check of our main findings we re-run our analysis on two additional data sets, (i) USD data for 5 different strike levels (ATM, ATM $\pm$ 50, ATM $\pm$ 100) and (ii) implied volatility data for at-the-money (ATM) swaptions on 2-year swap rates.

Table 11 reports USD summary statistics for the delta–vega and delta–gamma neutral strategies where the straddles are valued on an implied volatility data set with 5 different strike levels. For the delta–gamma neutral strategy we see that the average returns and Sharpe rations are higher than in our main findings (Table 4) for all maturity combinations. A possible explanation for the higher returns is that the strategy has positive vega exposure in combination typical higher out-of-the-money volatilities (smile or smirk pattern). For the delta–vega neutral strategy we observe a similar return and Sharpe ratio for the 3 vs 6-month strategy and slightly lower returns for the other two maturity combinations. Overall we conclude that our main findings are confirmed after controlling for the existence of an implied volatility smile or smirk.

Table 12 shows summary statistics for our trading strategies on the 2-year swap rate. On this data set, the patterns in the average returns are in general similar to the 10-year swap rate data, essentially showing positive returns that decrease in maturity. Yet, we note that average returns and Sharpe ratios are lower and in some case slightly negative. For the delta–gamma neutral strategy 10 out of 16 strategies have average returns that are statistically significant at the 10% level. For the vega-neutral strategy, the average USD and EUR returns are not statistically significant and 5 out of 8 strategies for the JPY and GBP. A potential explanation might come from Trolle and Schwartz (2014) who analyze the relationship between the tenor of the underlying swap rate and the variance risk premium. They document a hump-shaped function and report more negative returns for the 10-year tenor than for the 2-year tenor in both USD and EUR markets. We leave this issue for future work.

6. Economic importance

In this section we explore the economic importance of our findings. This is motivated by the findings of Santa-Clara and Saretto (2009), who show a large disparity between the profitability of option strategies in the equity market before and after taking costs into account. Transaction costs can be substantial and collateral requirements, to limit counterparty default risk, may further reduce profitability. Hence, the tensions in the funding markets during the Global Financial Crisis taught swaption dealers that funding costs embedded in derivative operations should not be ignored and might result in higher costs for investors.

We start from an investor's perspective. So far, the Sharpe ratios of our delta–gamma and delta–vega neutral strategies might look appealing to investors. Since the returns of both strategies are

Table 10
Summary statistics for trading strategies on SABR model.

		Delta neutral				Vega neutral			
		Mean (%)	*t*-stat	Stdev (%)	Sharpe	Mean (%)	*t*-stat	Stdev (%)	Sharpe
USD	3 vs 6	0.96	2.36	1.75	0.55	0.89	2.42	1.48	0.60
	6 vs 9	1.27	1.79	3.42	0.37	0.31	1.77	0.91	0.34
	9 vs 12	0.46	1.19	1.19	0.39	0.19	1.01	0.63	0.30
	3 vs 12	1.77	2.14	2.84	0.62	1.21	2.10	2.40	0.50

Note: This table reports annualized summary statistics of non-overlapping monthly returns on long-short swaption straddles strategies using the SABR model for hedging. The combined long-short straddles position either neutralizes the vega or the delta exposure according to the SABR greeks. The straddles are initiated on the last business day of the month. Summary statistics include annualized sample mean (Mean), annualized standard deviation (Stdev), skewness (Skew), kurtosis (Kurt), first-order autocorrelation (AC(1)), annualized Sharpe ratio and the percentage of months with a positive return (Hit). *t*-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

Table 11
Summary statistics for trading strategies on swaption smile.

		Gamma neutral				Vega neutral			
		Mean (%)	*t*-stat	Stdev (%)	Sharpe	Mean (%)	*t*-stat	Stdev (%)	Sharpe
USD	3 vs 6	1.50	3.31	1.64	0.91	0.89	2.39	1.49	0.60
	6 vs 9	0.89	3.40	1.01	0.88	0.29	1.71	0.92	0.31
	9 vs 12	0.62	3.43	0.57	1.08	0.18	0.92	0.64	0.28
	3 vs 12	3.76	3.48	3.71	1.01	1.19	2.06	2.42	0.49

Note: This table reports annualized summary statistics of non-overlapping monthly returns on long-short swaption straddles strategies for the USD market. Each month a swaption straddle with the lowest maturity is sold with a notional of one, and held for one month. At the same time an additional long straddle position, with a higher maturity, is bought at a notional that either neutralizes the vega or gamma exposure of the combined long-short position according to the Black (1976) model. The results differ from the results in Table 4 because swaption smile data is used to calculate the returns. Swaption data is available at 5 different strike levels (ATM, ATM ±50, ATM ±100). Summary statistics include annualized sample mean (Mean), *t*-statistics (*t*-stat), annualized standard deviation (Stdev) and annualized Sharpe ratio. *t*-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

Table 12
Summary statistics for trading strategies on 2-year tenor.

		Gamma neutral				Vega neutral			
		Mean (%)	*t*-stat	Stdev (%)	Sharpe	Mean (%)	*t*-stat	Stdev (%)	Sharpe
USD	3 vs 6	0.22	2.12	0.37	0.58	0.06	0.84	0.34	0.19
	6 vs 9	0.18	2.96	0.25	0.70	0.03	0.67	0.22	0.15
	9 vs 12	0.07	1.39	0.22	0.33	−0.04	−0.96	0.19	−0.23
	3 vs 12	0.61	2.48	0.98	0.62	0.06	0.48	0.55	0.11
EUR	3 vs 6	0.17	2.13	0.27	0.63	0.05	0.76	0.25	0.21
	6 vs 9	0.07	1.54	0.19	0.38	−0.01	−0.21	0.16	−0.06
	9 vs 12	0.09	2.18	0.17	0.52	0.03	0.62	0.17	0.15
	3 vs 12	0.44	2.23	0.68	0.64	0.05	0.48	0.40	0.14
JPY	3 vs 6	0.08	1.17	0.25	0.30	0.03	0.89	0.18	0.19
	6 vs 9	−0.02	−0.31	0.21	−0.09	−0.02	−0.80	0.12	−0.19
	9 vs 12	0.29	3.70	0.22	1.31	0.51	2.27	0.85	0.61
	3 vs 12	0.70	3.68	0.60	1.16	0.23	2.15	0.43	0.54
GBP	3 vs 6	0.07	0.82	0.30	0.24	0.15	1.80	0.28	0.53
	6 vs 9	0.07	1.23	0.22	0.30	0.07	1.44	0.21	0.34
	9 vs 12	0.10	2.19	0.19	0.54	0.08	1.83	0.16	0.48
	3 vs 12	0.35	1.68	0.72	0.48	0.23	1.79	0.45	0.51
EQW	3 vs 6	0.13	2.09	0.20	0.65	0.07	1.54	0.17	0.43
	6 vs 9	0.07	1.89	0.14	0.53	0.02	0.58	0.11	0.16
	9 vs 12	0.14	5.10	0.11	1.24	0.14	2.20	0.24	0.60
	3 vs 12	0.52	3.71	0.49	1.06	0.14	1.67	0.30	0.48

Note: This table reports annualized summary statistics of non-overlapping monthly returns on long-short swaption straddles strategies on a 2-year maturity of the underlying swap rate. Each month a swaption straddle with the lowest maturity is sold with a notional of one, and held for one month. At the same time an additional long straddle position, with a higher maturity, is bought at a notional that either neutralizes the vega or gamma exposure of the combined long-short position. The straddles are initiated on the last business day of the month. In addition to the USD, EUR, JPY and GBP markets, we compute the summary statistics of an equally-weighted (EQW) portfolio. Summary statistics include annualized sample mean (Mean), *t*-statistics (*t*-stat), annualized standard deviation (Stdev) and annualized Sharpe ratio. *t*-statistics are adjusted according to Newey and West (1987, 1994) to correct for heteroscedasticity and serial correlation up to four lags. The number of observations in each series is 189 and runs from April 1996 to December 2011.

positive (Table 4) and mutual correlations are low (Table 5), investors might consider combining the two strategies to benefit from diversification. Panel A in Table 13 reports the summary statistics for an equally weighted mix of the two strategies. Combining the two strategies proves to be successful, in the sense that returns are strongly significant and Sharpe ratios are higher for the combinations. For example, the return of the 3 vs 12-month maturity portfolio has a Sharpe ratio of 2.22 for the combined strategies compared to 1.35 and 0.95 for the individual delta–gamma and delta–vega neutral strategies respectively. In addition, Fig. 5 provides another way of presenting the combined results by plotting the cumulative wealth curves for the two individual strategies as well as the 50/50 combination. It is clear that all three curves show a positive drift. The combination, however, shows a further smoothing of the returns.

To study the left tail risks in the strategies' returns, we study the worst loss in any losing period during the historical simulation. This measure is called the maximum drawdown and is defined as the percent retrenchment from a peak-to-trough decline in the cumulative return. We analyze the worst three strategy drawdowns for the various countries and maturities in our data set. We focus on the 3 vs 12-month strategy, with the results of the

Table 13
Return statistics and break-even spread for the 3 vs 12-month mixed strategy.

	Panel A: 50/50 combination				Panel B: Break-even spread		
	Mean (%)	*t*-stat	Stdev (%)	Sharpe	Gamma neutr.	Vega neutr.	50/50 mix
USD	1.91	4.77	1.48	1.29	0.25	0.34	0.3
EUR	1.20	4.23	1.05	1.14	0.22	0.22	0.22
JPY	1.38	5.15	1.09	1.27	0.34	0.65	0.49
GBP	1.56	5.39	0.97	1.61	0.18	0.45	0.31
EQW	1.51	7.29	0.68	2.22	0.24	0.39	0.31

Note: This table shows summary statistics for a 50% delta–vega and 50% delta–gamma neutral mixed strategy (Panel A) and the break-even spread for the delta–gamma neutral, delta–vega neutral and mixed strategies respectively (Panel B) for the 3 vs 12-month strategy. The break-even spread is defined as the bid-offer implied volatility spread that makes the strategy unprofitable and expressed as implied volatility points.

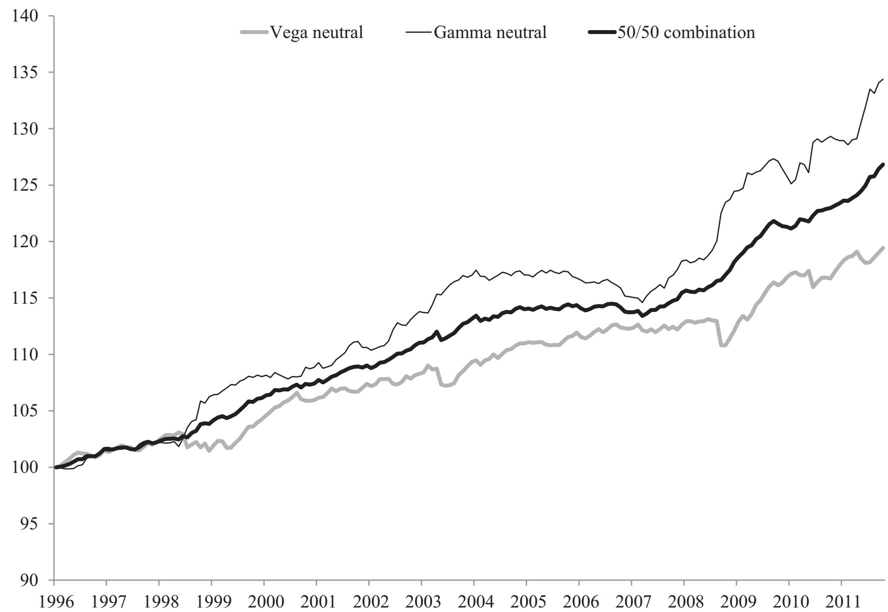


Fig. 5. Wealth curve swaption riding strategy. This figure shows the wealth curve of a long-short straddles strategies with swaption maturities of 3 months (short) and 12 months (long) respectively. Portfolio returns are the equally weighted (EQW) average returns for the USD, EUR, GBP and JPY markets.

other maturities generally being in line with this strategy. Table 14 presents the maximum drawdown and the time between the strategy's retrenchment until a new high is reached. For the vega neutral strategy, which is subject to jump risk, we observe large losses that coincide with the default of Russia in 1998 and the default of Lehman Brothers in 2008. For the gamma neutral strategy, which is subject to volatility risk, we observe the largest drawdowns during the steady decline of worldwide volatilities during 2004–2007. The 50/50 mix of the two strategies has much smaller drawdowns. The largest drawdown of the equally weighted country portfolio is less than 1%, which is less than a seventh of the largest drawdown that occurred in the gamma neutral strategy in the US.

Considering the economic significance we look at the break-even bid-offer spread for the 3 vs 12-month swaption maturity strategy. The break-even spread is defined as the bid-offer implied volatility spread that makes the strategy unprofitable and is expressed as implied volatility points. Panel B in Table 13 reports the break-even bid-offer spreads for the delta–gamma, delta–vega and combined strategies. The result shows that the break-even spreads for the equally weighted portfolio are 0.24, 0.39 and 0.31 volatility points for the delta–gamma, delta–vega and 50/50 mix strategies, respectively. These break-even spreads are within the bid-offer spreads in the market, which typically is 0.50 volatility points according to two major broker-dealers. This leads us to conclude that, taking into account trading costs, the returns of the delta–gamma, delta–vega and 50/50 mix strategies are not realizable by investors and therefore are not economically significant. This corroborates the findings for equity option strategies obtained by Santa-Clara and Saretto (2009).

The Global Financial Crisis and subsequent monetary policy decisions by central banks have caused derivative dealers to change their dealing practices. This might affect the profitability of our strategy. In particular, credit and liquidity risks are now recognized as having an impact on the economic value of a derivative security and have changed the manner in which derivative trades are conducted. First, the default of Lehman Brothers showed that counterparty credit risk cannot be ignored. Counterparty credit risk in a derivative trade should be carefully managed and either be priced or mitigated with the help of collateral. Today, derivative dealers make a credit value adjustment (CVA) in the pricing of a transaction to reflect the counterparty credit risk in uncollateralized transactions. On the other hand, fully collateralized transactions will rarely be subject to default risk and therefore CVA will be close to zero in these transactions. Second, banks became reluctant to lend to one other after the default of Lehman Brothers, and the subsequent liquidity squeeze made funding difficult and costly. For quite a while, derivative dealers were faced with a large gap between the funding costs of their institution and the risk-free rate in the option pricing model for trades that were not collateralized. This resulted in derivative dealers charging a funding value adjustment (FVA) to recover their funding costs. From Hull and White (2014) we know that the inclusion of FVA is a controversial issue that has resulted in much discussion between practitioners, academics and accountants. There are no simple solutions to the use of FVA because an FVA violates the law of one price in the market and can lead to conflicts between accountants and traders. Hull and White (2014) conclude that "an FVA is justifiable only for the part of a company's credit spread that does not reflect default risk." Overall, this gives rise to the question whether the profitability of our strategy is impacted by collateralized transactions and potential tensions on funding. We argue that the impact will be limited because in our long-short strategy both collateral as well as funding exposures will largely be set-off against one another.

To conclude, a remark on the economic importance should be made. Transaction costs have typically not been included in related literature on the volatility risk premium in general, nor interest rate derivatives specifically. For example, Trolle (2009) and Doran (2007) both indicate that more research in the direction of including trading and commission costs in the implementation could be done in future.[14]

Interestingly, our strategy framework motivates us to consider the economic importance of our results. Based on the results in this section we conclude that the returns of the delta–gamma and delta–vega neutral strategies are not realizable by investors.

[14] To our knowledge, the only exception is Duarte et al. (2007) who report returns that are statistically and economically significant for their strategy of selling interest rate volatility through delta-hedged caps.

Table 14
Maximum drawdowns for the 3 vs 12-month strategy.

		Gamma neutral			Vega neutral			50/50 combination		
		Drawdown (%)	#Months	Start	Drawdown (%)	#Months	Start	Drawdown (%)	#Months	Start
USD	Largest	−7.08	54	Mar 2004	−4.54	12	Oct 2008	−2.94	32	Jun 2005
	2nd largest	−3.61	10	Nov 2009	−4.42	21	Apr 2003	−2.04	14	Nov 2009
	3rd largest	−2.06	24	Oct 1996	−1.93	6	Jul 1998	−1.94	15	Mar 2004
EUR	Largest	−2.21	40	Jun 2005	−3.21	24	Jun 1998	−1.52	25	Nov 2006
	2nd largest	−1.94	15	Oct 2001	−2.61	28	Nov 2006	−1.20	18	Oct 2001
	3rd largest	−1.84	11	Aug 2010	−2.34	17	Jul 2010	−0.78	10	Dec 2005
JPY	Largest	−2.81	32	May 2000	−5.17	24	Apr 1998	−1.50	5	May 1999
	2nd largest	−2.36	28	Jun 2006	−2.74	10	Feb 2003	−1.40	16	May 2000
	3rd largest	−2.28	26	Oct 2009	−1.78	20	Jul 1996	−0.95	20	Jun 2006
GBP	Largest	−2.51	58	May 2003	−3.24	14	Apr 2008	−1.06	14	Nov 2006
	2nd largest	−2.12	19	Mar 1997	−1.52	6	Jun 2011	−0.90	11	Mar 1997
	3rd largest	−2.07	26	Aug 1999	−1.41	16	Nov 2006	−0.68	8	Jul 2000
EQW	Largest	−2.44	46	Mar 2004	−2.05	8	Aug 2008	−0.94	13	Oct 2006
	2nd largest	−1.74	9	Nov 2009	−1.63	10	Apr 2003	−0.67	5	Jun 2003
	3rd largest	−0.70	7	Dec 2001	−1.59	16	Jul 1998	−0.55	6	Nov 2009

Note: This table reports the three largest maximum drawdowns on the delta–gamma neutral, delta–vega neutral and mixed strategies for the 3 vs 12-month strategy. The maximum drawdown is defined as the worst cumulative loss in any losing period in the historical simulation (April 1996 to December 2011) of the strategy. The length of the drawdown (#Months) is the number of months between the strategy's retrenchment until a new high is reached in the cumulative strategy returns.

However, the goal of this paper is to identify the existence of a difference in the volatility risk premium across the term structure of fixed income derivatives. Our results support this for all four swaption markets.

7. Conclusion

Existing work has demonstrated that the volatility risk premium is more negative for short-term maturities than for longer maturities. However, while the existence of the volatility risk premium in the fixed income market has recently been analyzed by various papers, the maturity effect was only documented by Fornari (2010) and Mueller et al. (2013) and, to our knowledge, has not been analyzed in detail. Our paper contributes to the literature by providing a strategy framework to test and analyze the maturity effect in the volatility risk premium in fixed income markets. Specifically, we analyze the returns of two long-short straddle strategies which both 'ride' the swaption curve. The straddle combinations are either delta–vega neutral and subjected to jump risk, or delta–gamma neutral and subjected to volatility risk.

Using a large database (April 1996–December 2011) of implied volatility quotes of the four major bond markets, we find statistically significant returns, which incrementally decrease in swaption maturity for all markets. This finding is consistent with a concave, upward-sloping term structure in the volatility risk premium. The fact that both delta–vega and delta–gamma neutral strategies earn positive returns that seem uncorrelated suggests that the term structure of the volatility risk premium is affected by both jump risk and volatility risk. This effect seems most pronounced at shorter maturities. Additional robustness analysis indicates that the results seem robust when using the Vasicek (1977) and Hagan et al. (2002) SABR models instead of the Black model. The results are also robust for macroeconomic announcements, although we do observe a small effect for the day-of-the-month. Specifically, delta–vega neutral portfolios initiated around the turn of the month report higher returns than mid-month portfolios. Finally, our framework allows more detailed assessment of the economic importance. Transaction costs and margin requirements are typically not included in related literature on the volatility risk premium. Our break-even cost analysis points to the conclusion that the returns of the delta–gamma and delta–vega neutral strategies are not realizable by investors. This corroborates the findings for equity option strategies obtained by Santa-Clara and Saretto (2009). This limit may prevent markets from taking advantage of 'riding the swaption curve', but does not detract from our established conclusion that there is a statistically significant difference in the volatility risk premium across the swaption maturity term structure.

Since the maturity effect of the volatility risk premium seems to have received limited attention in the literature we encourage future research. A prominent issue that requires attention concerns the changes in the swaption market after the Global Financial Crisis. Prior to the crisis, swaption dealers relied on a single curve to forecast rates depending on an underlying index, eg LIBOR or Euribor, and to discount cash flows. The changes in market conditions and regulations have resulted in a different method for how swaptions are valued and risk is managed. In particular, a new multi-curve pricing framework that uses separate forecasting and discounting curves became market-standard for new swaption trades. Assuming mutual collateral agreements, the market has evolved toward discounting future cash flows using Overnight Index Swap (OIS) rates. The separation between the index rates and the OIS rates fundamentally changed the framework for swaption modeling. During the crisis the market slowly transitioned from the single curve methodology to the multi-curve methodology. For example, in September 2010 one of the leading international swaption dealers, ICAP, switched to OIS discounting and published both LIBOR- and OIS-based swaption implied volatilities. In January 2012 ICAP stopped publishing LIBOR-based volatilities and has since then only published OIS-based volatilities (Bianchetti and Carlicchi, 2013). January 2012 coincides exactly with the end of the empirical data set of this study. Further research using OIS-based swaption implied volatilities data post 2011 could give important complementary evidence on the consistency of our strategy. This investigation, however, lies beyond the scope of this paper.

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