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# Risk-Adjusted Option-Implied Moments


**Abstract**

Option-implied moments, like implied volatility, contain useful information about an underlying asset's return distribution, but are derived under the risk-neutral probability measure. This paper shows how to convert risk-neutral moments into the corresponding physical ones. The main theoretical result expresses moments under the physical probability measure in terms of observed option prices and the preferences of a representative investor. Based on this result, we investigate several empirical questions. We show that a model of a representative investor with CRRA utility can explain the variance risk premium for the S&P500 index but fails to capture variance and skewness risk premiums simultaneously. Moreover, we present methods to estimate forward-looking market risk premiums and investors' disappointment aversion implied in market prices.



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# I Introduction

The use of option prices to gain information about the underlying's return distribution is an important idea in finance. Certainly, the most prominent example is implied volatility that goes back to Latané and Rendleman (1976). More recent developments have moved forward from simple Black-Scholes volatilities to model-free implied volatilities (Britten-Jones and Neuberger (2000) and Jiang and Tian (2005)) and higher-order implied moments (Bakshi, Kapadia, and Madan (2003) and Neuberger (2012)). Implied moments are used extensively in a variety of applications, like forecasting (see the survey articles by Poon and Granger (2003), Christoffersen, Jacobs, and Chang (2012), and Giamouridis and Skiadopoulos (2012)), risk measurement (Buss and Vilkov (2012), Chang, Christoffersen, Jacobs, and Vainberg (2012), and Baule, Korn, and Saßning (2013)) and portfolio selection (Aït-Sahalia and Brandt (2008), Kostakis, Panigirtzoglou, and Skiadopoulos (2011), DeMiguel, Plyakha, Uppal, and Vilkov (2013), Kempf, Korn, and Saßning (2014), and Schneider (2014)).

Option-implied moments have the drawback that they are formed under the risk-neutral probability measure, whereas many applications require moments under the physical (real-world, actual, subjective) probability measure. Ideally, one would exploit all information contained in current option prices and have a simple but economically justified method to adjust for risk, i.e., to move from the risk-neutral moment to the corresponding physical moment. This paper provides such a method by showing explicitly how the risk adjustment depends on current option prices and risk preferences.

Our paper makes theoretical and empirical contributions. The main theoretical result shows how expected payoffs of call and put options under the physical measure depend on current option prices and the utility function of a representative investor. This result has many potential uses. A specific one is to express ex-ante return moments under the physical measure, which we call risk-adjusted implied moments, in terms of observed option prices and preferences. The presented methodology is very general. It applies to implied moments as in Neuberger (2012), implied moments as in Bakshi, Kapadia, and Madan (2003), which refer to log returns, and to the corresponding moments of discrete returns. It can deal with both central and non-central moments and is not restricted to a narrow class of utility functions.

The empirical contributions of the paper refer to different applications of the presented methodology for the S&P500 index. A first issue that we investigate is whether a model of a representative investor with CRRA utility can explain the variance risk premium and the skewness risk premium. We find that a specification with reasonable time variation in risk aversion is able to generate the variance risk premium, however, it fails to capture the variance and skewness risk premiums simultaneously. As a second empirical contribution, we derive a forward-looking market risk premium from a single cross section of option prices and find that the resulting premium has reasonable properties. Finally, we use preferences with disappointment aversion and present implied estimates of the corresponding parameter. These estimates indicate that disappointment aversion is time varying and often large enough to be economically significant.

Our paper relates to other work dealing with the connection between risk-neutral and risk-adjusted (ex-ante physical) moments. In principle, risk-adjusted implied moments can be obtained by transforming the full risk-neutral density into a physical density using certain preference assumptions. Such an approach, as followed by Rubinstein (1994), Bliss and Panigirtzoglou (2004), and Kostakis, Panigirtzoglou, and Skiadopoulos (2011),[1] adjusts all moments simultaneously. However, the construction of the full risk-neutral density causes numerical problems, in particular due to the need for numerical derivatives. It is a major advantage of the model-free implied moments according to Britten-Jones and Neuberger (2000), Bakshi, Kapadia, and Madan (2003), and Neuberger (2012) to circumvent these problems. The same advantage applies to the risk-adjusted implied moments presented in this

[1] These papers use a representative investor with a specific utility function. Ross (2013) develops an alternative approach by imposing restrictions on the dynamics of the stochastic discount factor. However, Borovicka, Hansen, and Scheinkman (2014) point out that the approach suffers from identification problems.

paper. An important result concerning the relation between risk-neutral and ex-ante physical moments is given in Bakshi, Kapadia, and Madan (2003). It states that the risk-neutral skewness can be approximated by the variance, skewness, and kurtosis under the physical probability measure and the preferences of a representative investor.[2] Bakshi and Madan (2006) provide a similar representation of the risk-neutral variance.[3] Our results differ from these previous ones as they apply to all moments of the return distribution, reverse the direction and describe physical moments in terms of current option prices and preferences, and deliver an exact characterization.

Another research area related to our paper is the study of variance and skewness risk premiums. It is a stylized fact that the variance risk premium is negative in the stock market (Coval and Shumway (2001), Bakshi and Kapadia (2003), and Carr and Wu (2009)). Kozhan, Neuberger, and Schneider (2013) show that the corresponding skewness risk premium is positive. Our work contributes to this literature by investigating in how far the risk aversion of a representative investor together with the market expectations contained in option prices can explain these phenomena.

Finally, our paper is related to studies about forward-looking market risk premiums and implied estimators of preference parameters. Duan and Zhang (2014) suggest an estimator of the ex-ante risk premium in the stock market that requires predictions of physical moments. We present an alternative based on a single cross section of option prices. Bliss and Panigirtzoglou (2004) exploit information from option prices to imply the relative risk aversion of the representative stock market investor. As an extension, we use this idea to obtain simultaneous estimates of risk aversion and disappointment aversion.

The remainder of the paper is organized as follows. In Section II we present our main theoretical result that links expected payoffs of call and put options to option prices and preferences. This result is applied in Section III to derive risk-adjusted implied

[2]See Theorem 2 in Bakshi, Kapadia, and Madan (2003).

[3]See Theorem 1 in Bakshi and Madan (2006).

moments. The following Section IV presents our data set and the way moments are computed. In Section V we provide some illustrations how risk aversion affects expected options payoffs and return moments. The results of different empirical applications are presented in Section VI. Section VII concludes.

# II Expected Payoffs Under the Physical Measure

Our analysis exploits the relation between physical and risk-neutral densities, as outlined, for example, by Aït-Sahalia and Lo (2000). Consider a risky asset with current price $S_t$, traded on a frictionless, dynamically complete market, and a risk-free asset with constant interest rate $r$. A representative investor exists and assigns utility $U(S_{t+\tau})$ to the future payoff $S_{t+\tau}$, $\tau > 0$, according to a utility function $U$. In such a setting, the relation between the physical density function, $p(S_{t+\tau})$, and the risk-neutral density function, $q(S_{t+\tau})$, is

$$p(S_{t+\tau}) = \frac{q(S_{t+\tau})}{c \cdot U'(S_{t+\tau})}, \qquad \text{with} \quad c \equiv \int \frac{q(x)}{U'(x)} dx. \tag{1}$$

Equation (1) shows how the physical density can be obtained from the knowledge of the risk-neutral density and the utility function of the representative investor. It is our goal to establish a similar link between expected payoffs of contingent claims under the physical measure, expected (discounted) options payoffs under the risk-neutral measure, i.e. option prices, and the utility function.

Define the expected discounted payoff of a call option (put option) with strike price $K$ and time to maturity $\tau$ under the physical measure as

$$C^P(t,\tau,K) \equiv E^P\left\{e^{-r\tau}(S_{t+\tau} - K)^+\right\}, \tag{2}$$

$$P^P(t,\tau,K) \equiv E^P\left\{e^{-r\tau}(K - S_{t+\tau})^+\right\}. \tag{3}$$

The following proposition shows how $C^P(t,\tau,K)$ and $P^P(t,\tau,K)$ can be expressed in terms of current options prices and the utility function.[4] The proof is provided in the appendix.

**Proposition 1.** *If the relation between physical and risk-neutral density is as in Equation (1) and the utility function of the representative investor is twice continuously differentiable with $U' > 0$ and $U'' < 0$, then*

$$C^P(t,\tau,K) = \frac{C(t,\tau,K)}{c \cdot U'(K)} + \int_K^\infty \frac{-U''(x)}{c \cdot U'(x)^2} \left\{ C(t,\tau,x) + (x-K)D(t,\tau,x) \right\} dx, \quad (4)$$

$$P^P(t,\tau,K) = \frac{P(t,\tau,K)}{c \cdot U'(K)} - \int_0^K \frac{-U''(x)}{c \cdot U'(x)^2} \left\{ P(t,\tau,x) + (K-x)(e^{-r\tau} - D(t,\tau,x)) \right\} dx, \quad (5)$$

$$\text{with } c = \int_0^\infty \frac{-U''(x)}{U'(x)^2} e^{r\tau} D(t,\tau,x) dx + \frac{1}{U'(0)},$$

*where $C(t,\tau,K)$ and $P(t,\tau,K)$ are the prices of call and put options, respectively, with strike price $K$ and time to maturity $\tau$. $D(t,\tau,K)$ denotes the price of a digital option that pays one dollar if $S_{t+\tau}$ is above the strike price $K$.*

The result in Proposition 1 is remarkable for several reasons. First, the expected (discounted) payoffs of both call and put options under the physical measure are expressed in terms of current prices of calls, puts and digital options, the risk-free interest rate, and the utility function only. Knowledge of the risk-neutral density is not required, which avoids severe numerical problems (see Bliss and Panigirtzoglou (2002) for a discussion of these issues, in particular the need for second derivatives of options prices with respect to the strike price). Instead, the expressions in Equations (4) and (5) can be obtained via stable numerical integration.

Second, the proposition shows a simple way to study the effects of risk-aversion on the returns of call and put options. If the utility function is linear, i.e., there is no risk aversion, Equations (4) and (5) confirm that $C^P(t,\tau,K) = C(t,\tau,K)$

[4] The required conditions on the utility are mild. It has to be twice continuously differentiable with $U' > 0$ and $U'' < 0$, which is fulfilled by most of the common utility functions, like the class discussed by Brockett and Golden (1987) and the HARA class.

and $P^P(t,\tau,K) = P(t,\tau,K)$. With growing risk aversion, however, the integrals on the right hand sides of Equations (4) and (5) gain importance. Since these integrals are always positive, it follows that risk aversion leads to $C^P(t,\tau,K) > C(t,\tau,K)$ and $P^P(t,\tau,K) < P(t,\tau,K)$, which is very intuitive. Because the payoff of a call option is positively related to the payoff of the underlying, higher risk aversion of the representative investor is associated with higher expected returns of calls. In contrast, for put options, payoffs are negatively related to the payoff of the underlying and higher risk aversion reduces the required expected returns. Finally, Proposition 1 can be used to express the expected payoffs of more general contingent claims in terms of option prices and the utility function of the representative investor, as stated in the following proposition.

**Proposition 2.** *Let $H(S_{t+\tau})$ be a twice continuously differentiable payoff function. Then the expected payoff $E^P\left[H(S_{t+\tau})\right]$ under the physical measure equals*

$$\begin{aligned} E^P\left[H(S_{t+\tau})\right] &= H(S_t) + H'(S_t)e^{r\tau}\left[C^P(t,\tau,S_t) - P^P(t,\tau,S_t)\right] \\ &\quad + e^{r\tau}\int_{S_t}^{\infty} H''(K)C^P(t,\tau,K)dK + e^{r\tau}\int_{0}^{S_t} H''(K)P^P(t,\tau,K)dK, \end{aligned} \tag{6}$$

*with $C^P(t,\tau,K)$ and $P^P(t,\tau,K)$ from Proposition 1.*

To prove Proposition 2, we exploit the spanning argument by Bakshi and Madan (2000) and Carr and Madan (2001). If $H$ is a twice continuously differentiable function, then $H(S_{t+\tau})$ equals

$$\begin{aligned} H(S_{t+\tau}) &= H(S_t) + (S_{t+\tau} - S_t)H'(S_t) \\ &\quad + \int_{S_t}^{\infty} H''(K)(S_{t+\tau} - K)^+dK + \int_{0}^{S_t} H''(K)(K - S_{t+\tau})^+dK. \end{aligned} \tag{7}$$

Now take expectations under the physical measure $P$ on both sides of Equation (7) and apply Fubini's theorem to obtain

$$
\begin{aligned}
E^P\left[H(S_{t+\tau})\right] &= H(S_t) + H'(S_t)E^P\left[(S_{t+\tau} - S_t)\right] \\
&\quad + e^{r\tau}\int_{S_t}^{\infty} H''(K)C^P(t,\tau,K)dK + e^{r\tau}\int_{0}^{S_t} H''(K)P^P(t,\tau,K)dK.
\end{aligned} \tag{8}
$$

Finally, note that $S_{t+\tau} - S_t = (S_{t+\tau} - S_t)^+ - (S_t - S_{t+\tau})^+$. Taking expectations yields $E^P\left[S_{t+\tau} - S_t\right] = e^{r\tau}\left[C^P(t,\tau,S_t) - P^P(t,\tau,S_t)\right]$.

□

Proposition 2 delivers the expected payoff of a contingent claim written on $S_{t+\tau}$ as a function of the current price $S_t$ of the underlying, current option prices, and the utility function of the representative investor. Since the same reasoning that led to Equation (6) applies under the risk neutral measure (see Bakshi, Kapadia, and Madan (2003)), we obtain the following ex-ante risk premium of the contingent claim:

$$
\begin{aligned}
E^P\left[H(S_{t+\tau})\right] &- E^Q\left[H(S_{t+\tau})\right] = \\
&H'(S_t)e^{rt}\left[(C^P(t,\tau,S_t) - C(t,\tau,S_t)) - (P^P(t,\tau,S_t) - P(t,\tau,S_t))\right] \\
&+ e^{rt}\int_{S_t}^{\infty} H''(K)(C^P(t,\tau,K) - C(t,\tau,K))dK \\
&+ e^{rt}\int_{0}^{S_t} H''(K)(P^P(t,\tau,K) - P(t,\tau,K))dK.
\end{aligned} \tag{9}
$$

The above risk premium considers the whole distribution of $S_{t+\tau}$, conditional on the information available at time $t$. In particular, it takes all moments of the underlying's price distribution into account and does not require any stationarity assumption for the price process. This is achieved by exploiting the information in current option prices. Such ex ante risk-premia have many potential applications, for example, the performance measurement of portfolio strategies with options. In this paper, however, our goal is to study appropriate risk adjustments and risk premiums for moments of the return distribution.

# III Moments Under the Physical Measure

Different moments of the return distribution result from different choices of the function $H(S_{t+\tau})$. Table 1 shows some important cases. It provides the specific choice of the function $H(S_{t+\tau})$, the required values of $H(S_t)$, $H'(S_t)$, and $H''(K)$, and the resulting expression for the risk-adjusted implied moment. Such a moment is a model-free implied one in the sense that it exploits information from current options prices without reference to a specific option pricing model. It is model dependent, however, because of its reliance on the specific utility function of the representative investor. As the realized moment, it is taken under the physical measure. In contrast to the realized one, however, that exploits ex-post realized prices, it is an ex-ante moment. For simplicity, we call it the ex-ante physical moment or just the physical moment.

*[ Insert Table 1 about here ]*

Panel A of Table 1 considers variance and skewness measures from Neuberger (2012), who suggests $2E(\frac{S_{t+\tau}}{S_t} - 1 - \ln\frac{S_{t+\tau}}{S_t})$ as a generalized variance and $6E(2 + \ln\frac{S_{t+\tau}}{S_t} - 2\frac{S_{t+\tau}}{S_t} + \frac{S_{t+\tau}}{S_t}\ln\frac{S_{t+\tau}}{S_t})$ as an approximation of the third (non-central) moment of log returns. The motivation for these moment measures is their aggregation property. Aggregation guarantees that higher frequency data can be used to obtain unbiased estimates of the physical moment over the return period from $t$ to $t+\tau$. The aggregation property helps us to study the relation between implied moments under the risk-neutral measure (as given in Kozhan, Neuberger, and Schneider (2013)), the corresponding ex-ante physical moments (as given in Table 1), and the corresponding realized moments.

Panel B considers higher non-central moments ($k \geq 2$) of log returns. The corresponding risk-neutral model-free implied moments were derived by Bakshi, Kapadia, and Madan (2003) and are widely applied. For some applications, however, like portfolio optimization, we require moments of discrete returns instead of log returns. Therefore, Panel C considers discrete returns.[5]

To obtain central moments, we additionally need to express the expected return in terms of vanilla option prices and the utility function. Consider discrete returns first. Since $S_{t+\tau} - S_t = (S_{t+\tau} - S_t)^+ - (S_t - S_{t+\tau})^+$, the expected return equals

$$\begin{aligned} E^P\left[\frac{S_{t+\tau} - S_t}{S_t}\right] &= E^P\left[\frac{(S_{t+\tau} - S_t)^+}{S_t}\right] - E^P\left[\frac{(S_t - S_{t+\tau})^+}{S_t}\right] \\ &= \frac{e^{rt}}{S_t}\left(C^P(t,\tau,S_t) - P^P(t,\tau,S_t)\right). \end{aligned} \tag{10}$$

For log returns, apply the spanning argument by Bakshi and Madan (2000) and Carr and Madan (2001) again. With $H(S_{t+\tau}) = \log \frac{S_{t+\tau}}{S_t}$, we obtain $H(S_t) = 0$, $H'(S_t) = \frac{1}{S_t}$, and $H''(K) = -\frac{1}{K^2}$, leading to[6]

$$\begin{aligned} E^P\left[\log\frac{S_{t+\tau}}{S_t}\right] &= \frac{e^{rt}}{S_t}\left(C^P(t,\tau,S_t) - P^P(t,\tau,S_t)\right) \\ &\quad - e^{rt}\int_{S_t}^{\infty} \frac{1}{K^2} C^P(t,\tau,K)dK - e^{rt}\int_{0}^{S_t} \frac{1}{K^2} P^P(t,\tau,K)dK. \end{aligned} \tag{11}$$

The results in Table 1 are useful for different purposes. An immediate application is the prediction of moments, like the variance, for use in risk management or portfolio optimization. Information from current option prices has been shown to be very useful in this respect.[7] However, what is needed are predictions under the physical measure. Our results show how to use option-implied information in combination with an assumption about risk preferences to arrive at the required predictions.

Another application concerns the understanding of risk premiums. Because the risk-neutral counterparts of $E^P\left[H_{t+\tau}\right]$ are readily available (one simply has to replace $C^P$ and $P^P$ by the corresponding call and put prices), the results in Table 1 allow

[5] See Christoffersen, Jacobs, and Chang (2012) for a presentation of the corresponding risk-neutral model-free implied moments.

[6] See Jiang and Tian (2005) for the corresponding result under the risk-neutral measure.

[7] See the survey articles by Poon and Granger (2003) and Christoffersen, Jacobs, and Chang (2012).

us to express the ex-ante risk premium contained in physical moments in terms of current prices (spot price and option prices) and risk aversion (see Equation (9)). Finally, we can reverse the procedure and use the results in Table 1 to obtain implied estimates of the representative investor's preferences. Such empirical applications will be presented in Section VI.

# IV Data and Moment Calculations

The options data set for our empirical analyses consists of European options written on the S&P500 spot index traded on the CBOE. The data source is OptionMetrics, and the data period covers January 1996 to December 2011. We use the one month put and call options that mature every month. Matching interest rates and spot prices of the underlying are also provided by OptionMetrics.

The analyses concentrate on the variance measure $2E(\frac{S_{t+\tau}}{S_t} - 1 - \ln \frac{S_{t+\tau}}{S_t})$ and the skewness measure $6E(2 + \ln \frac{S_{t+\tau}}{S_t} - 2\frac{S_{t+\tau}}{S_t} + \frac{S_{t+\tau}}{S_t} \ln \frac{S_{t+\tau}}{S_t})$ from Neuberger (2012). The major advantage of these measures is the availability of realized moments for both variance and skewness[8] in addition to the risk-neutral and physical moments.

The computation of risk-neutral and physical moments (according to Table 1 and Equations (4) and (5)) follows a standard procedure, as outlined, for example, by Chang, Christoffersen, Jacobs, and Vainberg (2012). For every month in the data period, we select the first trading day after the expiration day of expiring options contracts at CBOE. This choice guarantees the existence of options series with times to expiration close to the one month time horizon that we use. We take the implied Black-Scholes volatilities provided by OptionMetrics of all out-of-the money put and call options and fit a cubic spline to obtain a smooth volatility curve. Outside the available range of strike prices the volatility curve is assumed to be flat. Then we select 1500 equally spaced strike prices on the interval $[1.001, 3 \cdot S_t]$. For these 1500 strike prices, the corresponding implied volatilities are converted back into option

[8]For the standard definition of skewness, it is quite unclear what a reasonable realized moment would be.

prices via the Black-Scholes formula. As we don't have market prices for digital options available, we use the same volatility curves and a Black-Scholes type formula to obtain prices. With these option prices, we calculate the implied moments under the risk-neutral measure and, given a parametrization of the utility function, under the physical measure.

The computation of realized variance and skewness follows Kozhan, Neuberger, and Schneider (2013). For the return period starting at time $t$ and ending at time $t+\tau$, which is one month in our study, all daily returns within this period are used for the calculations. Let $n$ be the number of days in the return period and $r_i$ be the log return of the index at day $i$. Then the realized variance $rv_{t,t+\tau}$ and the realized skewness $rs_{t,t+\tau}$ are

$$rv_{t,t+\tau} = \sum_{i=1}^{n} 2(e^{r_i} - 1 - r_i), \tag{12}$$

$$rs_{t,t+\tau} = \sum_{i=1}^{n} 3\delta v^E_{i,t+\tau}(e^{r_i} - 1) + 6(2 - 2e^{r_i} + r_i + r_i e^{r_i}), \tag{13}$$

where $\delta v^E_{i,t+\tau}$ is change from day $i-1$ to day $i$ of another volatility measure, called the variance of the entropy contract, that is calculated from the cross section of option prices each day and refers to the period until $t+\tau$.[9] Because skewness is usually reported as a standardized measure, we follow this practice and finally calculate $rskew_{t,t+\tau} = rs_{t,t+\tau}/(rv_{t,t+\tau})^{3/2}$.

# V The Impact of Risk Aversion on Expected Option Payoffs and Moments

Propositions 1 and 2 provide a basis to study the impact of risk aversion on expected options payoffs and ex-ante physical moments. The resulting effects should depend on the current market situation, i.e., expectations about the return distribution. In

[9] See Kozhan, Neuberger, and Schneider (2013) for details.

our approach, these expectations are captured by the cross section of current option prices. Assume that the representative investor's utility of wealth $W$ is expressed by a CRRA utility function

$$U(W) = \begin{cases} \frac{W^{1-\gamma}-1}{1-\gamma} & \text{if} \quad \gamma \neq 1 \\ \log(W) & \quad\quad\; \gamma = 1 \end{cases}, \tag{14}$$

where $\gamma$ is the coefficient of relative risk aversion. Moreover, as an example, consider the market conditions (observed prices) on 20/01/2004, which is the midpoint of our data sample. Figure 1 shows how the expected payoffs of options written on the S&P500 index change with risk aversion under these market conditions. The horizontal axis depicts different strike prices. To the right of the forward price (1138.23), the expected payoffs refer to call options; to the left of the forward price, they refer to put options.

*[ Insert Figure 1 about here ]*

As expected, a higher risk aversion leads to higher expected payoffs for calls and lower expected payoffs for puts. The representative investor requires a higher return of call options and a lower return of put options with increasing risk aversion. However, the effects on calls and puts are not symmetric. Moving from risk neutrality to relative risk aversion of 2 or 4 has a much stronger effect on puts than on calls. Even put options that are far out-of-the money react to the change in risk aversion, whereas the corresponding call options show almost no effect. The reason for such a different reaction is that current option prices can capture asymmetries in the return distribution. Therefore, Figure 1 highlights the importance of conditioning on current market information when studying risk premiums and risk adjustments.

A similar analysis can be done for variance and skewness. Figure 2 shows how the ex-ante physical moments change with different levels of risk aversion. Again, the data refers to 20/01/2004. As a reference point, it is instructive to recall what would happen under a log-normal price distribution. In this case risk aversion has no effect on either variance or skewness.[10] Figure 2, however, shows a significant effect. Therefore, current option prices provide an indication for a non-normal return distribution.

*[ Insert Figure 2 about here ]*

When looking at variance, two effects are worth mentioning. First, because the risk-neutral variance (x 100) is 0.213, the ex-ante physical variance is below the risk-neutral one for all levels of risk aversion between 1 and 12. In such a situation the representative investor model with CRRA utility holds at least some promise as a potential explanation of a negative variance risk premium, a point we will further explore in the next section. Second, the ex-ante variance is not a monotonic function of the risk aversion, but has a minimum at a relative risk aversion of 5.25.

The ex-ante skewness generally increases with $\gamma$, starting from a negative value of -2.010 for a risk-neutral investor to a positive value of 1.716 for an investor with $\gamma = 12$. Therefore, the representative investor model predicts a positive skewness risk premium. Moreover, ex-ante skewness seems to be quite sensitive to the level of risk aversion.

The results in Figure 2 refer only to a single date, but the main observations hold more generally for the whole data set. Table 2 provides some descriptive statistics for all 192 months in the sample. Panel A refers to the variance and Panel B to the skewness.

*[ Insert Table 2 about here ]*

When looking at either the mean, the median or the quartiles Q1 and Q3, we see that the variance is first decreasing with risk aversion and than increasing. On average, the minimum is reached between 2 and 3, which is a reasonable estimate of the overall level of investors' risk aversion. In contrast to the variance, skewness is generally increasing with $\gamma$. For both variance and skewness, there is a substantial variation over time for any fixed level of risk aversion.

[10] See Bakshi, Kapadia, and Madan (2003), p.110.

# VI Empirical Applications

## A Variance Risk Premium

A first question that we address empirically is whether the model of a representative investor with CRRA utility can explain the variance risk premium, i.e., the difference between realized variance and implied risk-neutral variance. A crucial issue for the analysis of this question is the choice of the risk aversion parameter $\gamma$. Our approach allows for a time-varying $\gamma$ and exploits the model's full potential to create ex-ante premiums. If in this setting the ex-post variance risk premium is still more negative than the ex-ante one, we can conclude that the model is unable to provide a full explanation.

Specifically, we restrict possible values of $\gamma$ to the interval $[1, 10]$. For each month in the data period we then select the value of $\gamma$ that leads to the lowest ex-ante physical variance. For example, on 20/01/2004, the corresponding $\gamma$ equals 5.25 (see Figure 2). Figure 3 shows how the resulting $\gamma$ values evolve over time. They fall into a reasonable range and only rarely take the extreme values of 1 or 10 (23 out of 192 cases). There is also a specific time pattern. From 1996 to 2003, $\gamma$ mainly decreases. It subsequently increases until the beginning of the financial crisis in mid 2007 and then drops rapidly during the crisis. After the crisis, there is an increase again.

The $\gamma$ values in Figure 3 are implied from information in option prices and exploit the capability of the model to produce low values of the ex-ante physical variance. Neither historical nor expected index returns were used. Nevertheless, the resulting $\gamma$s have an intuitive interpretation in terms of the expected compensation per unit of risk. If $\gamma$ is high, investors expect a high risk compensation in the market, if it is low, there is only little compensation. When looking at periods of market downturn, $\gamma$ clearly declines after the burst of the internet bubble from 2000 to early 2003 and during the financial crisis. Therefore, investors judge the risk-return trade-off in the stock market as rather bad in periods of market downturn and high volatility (low

$\gamma$). Those who remain invested in the stock market during such periods, however, are willing to accept such a trade-off, which nevertheless offers high expected profits due to the high risk. In periods when markets grow steadily, investors see the risk-return trade-off more favorably (high $\gamma$) and those invested in the stock market during these periods require a higher compensation per unit of risk.

*[ Insert Figure 3 about here ]*

Figure 4 shows the impact of the resulting risk adjustment on implied variances. It depicts the risk-neutral variance (dashed line) and the ex-ante physical variance (dotted line). Except for six months, the risk-neutral variance is always higher than the physical one. The effect can be very substantial, since the risk-neutral variance equals more than twice the physical one in some extreme cases. In addition to the ex-ante implied variances (risk-neutral and physical), Figure 4 shows the ex-post realized variance (solid line). The relation between the risk-neutral and the realized variance follows a well known pattern. Usually, the risk-neutral variance is much higher than the realized one, leading to a negative variance risk premium on average. In some months, however, the realized variance has extreme spikes and greatly exceeds the risk-neutral variance, like in August 1998, July 2002, September 2008, and October 2008.

*[ Insert Figure 4 about here ]*

Panel A of Table 3 provides descriptive statistics for the three variances (realized, risk-neutral, and physical). A comparison of the means shows that the difference between realized and risk-neutral variance is on average -0.099, a clearly negative variance risk premium. The risk-adjustment via the representative investor model can fully explain this difference, however. As given in the last row, the mean difference between realized and physical variance is even slightly positive (0.004). The descriptive statistics also confirm that the realized variance has a much higher variability over time than the risk-neutral and physical ones due to the spikes. Moreover, the variability of the physical variance is smaller than the variability of the risk-neutral one, i.e., moving from the physical measure to the risk-neutral one increases the time variation of ex-ante implied variances.

*[ Insert Table 3 about here ]*

## B Forward-Looking Market Risk Premium

Risk-adjusted option-implied moments offer a simple way to obtain forward-looking measures of the market risk premium. The market risk premium is a central quantity in finance but difficult to measure, because it is an ex-ante concept. In periods of market downturn, in particular, mean excess returns of a market index may not be appropriate estimates of the premium. To overcome this problem, Duan and Zhang (2014) develop a forward-looking measure based on higher moments of the return distribution in a framework with a representative investor with CRRA utility of end-of-period wealth. However, implementation requires, in addition to the risk-neutral variance, predictions of the ex-ante physical second to fourth moments, obtained from a time series model.[11]

An alternative approach that does not require any time series data but just a cross section of option prices starts from Equations (10) and (11). These equations express the expected market return under the physical measure in terms of option prices and the risk aversion of the representative investor. Subtracting the corresponding expected returns under the risk-neutral measure provides the forward-looking market risk premium. The only missing information is the risk aversion, which can be obtained as in the previous subsection (see Figure 3).[12]

*[ Insert Figure 5 about here ]*

[11] Duan and Zhang (2014) use an $NGARCH(1,1)$ model for their empirical analysis.

[12] An alternative $\gamma$ estimate would be the value that minimizes the mean (absolute or squared) difference between the ex-ante variance and the realized variance over some historical data period, for example a 5-year moving window as in Duan and Zhang (2014). This procedure would require historical returns to calculate realized variance. However, there is still no need to specify any time series model to predict higher moments under the physical measure, because expectations about the return distribution are already captured by current option prices.

Figure 5 shows how the resulting forward-looking market risk premium evolves over time. The corresponding descriptive statistics are given in Panel B of Table 3. A first observation is that the market risk premium is almost always positive, as one would reasonable expect for an ex-ante premium. There are only two exceptions (November 2005 and February 2007), but the values are very small. On average, the forward-looking market risk premium is about one percentage point per month. This value seems to be high compared with realized premiums. One has to keep in mind, however, that the ex-ante premium is almost always positive in contrast to the realized one.[13] A second observation is a substantial variation of the market risk premium over time. It results from the time variation of both risk aversion and risk-neutral implied distributions. Finally, we observe that the market risk premium is high during periods of turmoil, like in October 2008 and May 2010. The reason is not a high risk aversion, as we have seen in the previous subsection, but simply very high risk.

## C Skewness Risk Premium

An ideal model would not only explain the variance risk premium but simultaneously the skewness risk premium (and any other risk premium associated with even higher moments). As we have seen in Subsection A, a CRRA model with time-varying risk aversion leads to an ex-ante variance risk premium that closely resembles the ex-post realized one on average. With the same $\gamma$ parameters, however, the model does not well explain the skewness risk premium.

Panel C of Table 3 gives the corresponding results. The means and the medians show that realized skewness is less negative than risk-neutral skewness on average, leading to a positive skewness risk premium. In contrast to the other two skewness measures, the ex-ante physical skewness is positive on average, causing a large negative difference between the realized and the ex-ante physical ones. Clearly, the risk adjustment suggested by the model is much too strong. This finding does not mean,

[13] The average forward-looking market risk premium reported by Duan and Zhang (2014), p.528, is even higher.

however, that a representative investor model with CRRA utility can't explain the skewness risk premium. It simply means that the $\gamma$ parameters that lead to a disappearing variance risk premium are too high for an appropriate skewness adjustment. The model can't explain variance and skewness risk premiums simultaneously. One way to proceed would be the use of more general utility functions, exploiting the flexibility allowed by Propositions 1 and 2. The next subsection provides an example of such a more general function.

## D Implied Disappointment Aversion

Preferences with disappointment aversion, as introduced by Gul (1991), have received growing attention in finance. Disappointment aversion builds on the idea that investors weight losses more heavily than gains, like in prospect theory. However, disappointment aversion has an axiomatic foundation and is easier to apply to portfolio problems.[14] Applications of disappointment aversion comprise the classical problem of allocating funds between stocks and bonds (Ang, Bekaert, and Liu (2005)), the study of economic benefits from giving investors access to options (Driessen and Maenhout (2007)), and the analysis of market timing strategies (Kostakis, Panigirtzoglou, and Skiadopoulos (2011)). Although these studies provide important results on the effects of disappointment aversion, very little is known about the magnitude of disappointment aversion and its estimation from market data.

Our analysis follows the general idea of Bliss and Panigirtzoglou (2004) to imply preference parameters from option prices. A utility function with disappointment aversion,[15] as shown in Equation (15), has two such parameters: $\gamma$ is the coefficient of relative risk aversion and $A \leq 1$ the coefficient of disappointment aversion. In addition, the forward price $F_{t,t+\tau}$ serves as the reference point for the definition of

[14] See Ang, Bekaert, and Liu (2005), Section 4, for a discussion of the differences between the two concepts.

[15] The utility function with disappointment aversion is not differentiable at $W = F_{t,t+\tau}$, which violates the requirements of Proposition 1. It is no problem, however, to approximate the utility function in a small interval around $F_{t,t+\tau}$ with a twice continuously differentiable function. That is how we proceed.

losses.[16]

$$U(W) = \begin{cases} \frac{W^{1-\gamma}-1}{1-\gamma} & \text{if} \quad W > F_{t,t+\tau} \\ \frac{W^{1-\gamma}-1}{1-\gamma} - \left(\frac{1}{A}-1\right)\left[\frac{F_{t,t+\tau}^{1-\gamma}-1}{1-\gamma} - \frac{W^{1-\gamma}-1}{1-\gamma}\right] & \quad\quad W \leq F_{t,t+\tau} \end{cases}. \quad (15)$$

With $A = 1$, the above utility function reduces to CRRA, and the lower $A$, the higher the disappointment aversion. We use the return skewness to estimate $\gamma$ and $A$, because it is crucial for investors who value gains and losses differently, and select the parameter combination that leads to an average skewness risk premium closest to zero over a rolling estimation window of 12 months. The result is a series of estimates for the period from December 1996 to December 2011. Figure 6 shows the development of the risk aversion parameters over time. Panel D of Table 3 presents the corresponding descriptive statistics.

*[ Insert Figure 6 about here ]*

The descriptive statistics show that $\gamma$ is usually rather low with a mean of 0.5. This result is in line with the findings about the variance risk premium and the skewness risk premium. A matching of ex-ante physical skewness and realized skewness requires a much lower risk aversion of the representative investor than a matching of the corresponding variances. The magnitude of the implied disappointment aversion $A$ is particularly interesting. With a mean close to 0.85, the disappointment aversion is large enough to be economically significant. Ang, Bekaert, and Liu (2005) show that for realistic data generating processes $A = 0.85$ leads to a reasonable allocation of stocks and bonds in the classical portfolio problem.

Another observation from Figure 6 is that both $\gamma$ and $A$ vary over time. Periods of high risk aversion are usually also periods of high disappointment aversion. The disappointment aversion of the representative stock market investor clearly declines

[16] In general, the reference point is the implicitly defined certainty equivalent wealth that depends on the endogenously determined portfolio. Since the representative investor holds the market, the certainty equivalent equals the forward price.

(growing $A$) in periods of market downturn from 2000 to early 2003 and during the financial crisis. This finding is consistent with the view that investors with high disappointment aversion left the stock market during these periods.

# VII Conclusions

This paper presents an exact characterization of the expected payoffs of call and put options under the physical probability measure in terms of current option prices and the preferences of a representative investor. The result allows us to exploit the full information contained in current prices to study the effects of risk preferences on the expected performance of options. It could help to define proper benchmarks for measuring the performance of trading strategies with options. It could also be useful for the design of structured products, because one can study a product's required return for different groups of investors (with different risk preferences) in a current market situation.

An important application of our major theoretical result is the risk adjustment of option-implied moments. We show explicitly how the risk adjustment that transforms risk-neutral into physical moments can be done. The theoretical results build the basis for different empirical applications. We find that the model of a representative CRRA investor with reasonable time variation in the coefficient of relative risk aversion can explain the variance risk premium for the S&P500, but fails to capture the variance and skewness risk premiums simultaneously. Moreover, we demonstrate how a forward-looking market risk premium can be obtained from a single cross section of option prices and find that the resulting premium has reasonable properties. Finally, we provide implied estimates of the overall disappointment aversion in the stock market, which are economically significant in many periods.

Several open issues should be explored in future research. An important task is to find specifications of the utility function that are best suited to improve volatility predictions. Another issue concerns the search for a model that explains both variance and skewness risk premiums (and potentially premiums associated with even higher moments). A related question is the simultaneous explanation of risk premiums for different assets. This task would require an extension of the theory, however, because it is an open question how the risk adjustment for the whole market translates into a corresponding risk adjustment for individual assets.

# Appendix

To prove Proposition 1, we use Equation (1) and the following result from measure theory[17]:

*Let $(\Omega, \mathcal{A}, \mu)$ be a finite measure space, $f$ a non-negative, real-valued measurable function, and $\varphi : [0,\infty) \to [0,\infty)$ a continuously differentiable and monotonically increasing function with $\varphi(0) = 0$. Then*

$$\int \varphi \circ f \, d\mu \; = \int_0^\infty \varphi'(x)\, \mu(f > x)\, dx. \tag{16}$$

Since $U$ is twice continuously differentiable, the function $\frac{1}{U'(x)}$, $x \in [0,\infty)$, has the following properties:

(i) $\frac{1}{U'(x)}$ is continuously differentiable, since it is a composition of continuously differentiable functions,

(ii) $\frac{1}{U'(x)}$ is monotonically increasing for all $x > 0$, since $\left(\frac{1}{U'(x)}\right)' = \frac{-U''(x)}{U'(x)^2} > 0$,

(iii) for $x \to 0$, $\frac{1}{U'(x)}$ reaches its minimum and converges to a non-negative value. Therefore, $\frac{1}{U'(x)}$ is a non-negative function.

It follows that $\frac{1}{U'(x)} - \frac{1}{U'(0)}$ satisfies all conditions required for $\varphi$, where $\frac{1}{U'(0)}$ stands for $\lim\limits_{x\to 0} \frac{1}{U'(x)}$.

The discounted expected payoff of a call option under the physical measure equals

$$\begin{aligned} C^P(t,\tau,K) &= E^P\left\{e^{-r\tau}(S_{t+\tau} - K)^+\right\} \\ &= \int_0^\infty e^{-r\tau}(S_{t+\tau} - K)^+ P(dS_{t+\tau}). \end{aligned}$$

[17] See Satz 19.13 in Alsmeyer (2003). Special cases of this result where $\mu$ is a probability measure and $f$ is a random variable can be found in many textbooks, e.g., Lemma 6.1. in Feller (1971), p.150.

Using the relation between physical and risk-neutral measure from Equation (1) yields

$$
\begin{aligned}
&\frac{1}{c}\cdot\int_0^\infty e^{-r\tau}(S_{t+\tau}-K)^+\frac{1}{U'(S_{t+\tau})}Q(dS_{t+\tau})\\
&=\frac{1}{c}\cdot\int_0^\infty\left\{\frac{1}{U'(S_{t+\tau})}-\frac{1}{U'(0)}+\frac{1}{U'(0)}\right\}\underbrace{e^{-r\tau}(S_{t+\tau}-K)^+Q(dS_{t+\tau})}_{\equiv\mu_C(dS_{t+\tau})},
\end{aligned}
$$

where $\mu_C$ defines a measure. We can now apply the above result from measure theory, which leads to

$$
\begin{aligned}
C^P(t,\tau,K)&=\frac{1}{c}\cdot\int_0^\infty\frac{-U''(x)}{U'(x)^2}\mu_C\{S_{t+\tau}>x\}dx+\frac{C(t,\tau,K)}{c\cdot U'(0)}\\
&=\frac{1}{c}\cdot\int_0^\infty\frac{-U''(x)}{U'(x)^2}\left\{\int_x^\infty e^{-r\tau}(S_{t+\tau}-K)^+Q(dS_{t+\tau})\right\}dx+\frac{C(t,\tau,K)}{c\cdot U'(0)}.
\end{aligned}
$$

For $x<K$, the inner integral $\int_x^\infty e^{-r\tau}(S_{t+\tau}-K)^+Q(dS_{t+\tau})$ equals the value of a plain-vanilla call option with strike price $K$. For $x>K$, it follows that

$$
\begin{aligned}
&\int_x^\infty e^{-r\tau}\underbrace{(S_{t+\tau}-K)^+}_{>0}Q(dS_{t+\tau})\\
&=\int_x^\infty e^{-r\tau}(S_{t+\tau}-x)Q(dS_{t+\tau})+\int_x^\infty e^{-r\tau}(x-K)Q(dS_{t+\tau})\\
&=C(t,\tau,x)+(x-K)e^{-r\tau}Q\{S_{t+\tau}>x\}\\
&=C(t,\tau,x)+(x-K)D(t,\tau,x),
\end{aligned}
$$

where $D(t,\tau,x)$ denotes the price of a digital option that pays one dollar if $S_{t+\tau}>x$. Finally, we obtain the following expression:

$$
C^P(t,\tau,K)=\frac{1}{c}\cdot\int_0^\infty\frac{-U''(x)}{U'(x)^2}C(t,\tau,K)1_{\{x<K\}}dx+\frac{C(t,\tau,K)}{c\cdot U'(0)}
$$

$$
\begin{aligned}
&+ \frac{1}{c} \cdot \int_0^\infty \frac{-U''(x)}{U'(x)^2} \left\{ C(t,\tau,x) + (x-K) D(t,\tau,x) \right\} 1_{\{x>K\}} dx \\
&= \frac{1}{c} \cdot C(t,\tau,K) \left\{ \frac{1}{U'(K)} - \frac{1}{U'(0)} \right\} + \frac{C(t,\tau,K)}{c \cdot U'(0)} \\
&+ \frac{1}{c} \cdot \int_K^\infty \frac{-U''(x)}{U'(x)^2} \left\{ C(t,\tau,x) + (x-K) D(t,\tau,x) \right\} dx.
\end{aligned}
$$

The expression for the constant $c$ can be derived in a similar way:

$$
c \;=\; \int_0^\infty \left\{ \frac{1}{U'(S_{t+\tau})} - \frac{1}{U'(0)} + \frac{1}{U'(0)} \right\} Q(dS_{t+\tau}).
$$

Applying the above result from measure theory to the measure $Q$ yields

$$
\begin{aligned}
c &= \int_0^\infty \frac{-U''(x)}{U'(x)^2} \left\{ \int_x^\infty Q(dS_{t+\tau}) \right\} dx + \frac{1}{U'(0)} \\
&= \int_0^\infty \frac{-U''(x)}{U'(x)^2} e^{r\tau} D(t,\tau,x) dx + \frac{1}{U'(0)}.
\end{aligned}
$$

The proof for the expected discounted payoff of a put option proceeds in the same way.

$\square$

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**Table 1:** Physical Moments as Functions of Option Prices

| $H(S_{t+\tau})$ | $H(S_t)$, $H'(S_t)$, $H''(K)$ | $E^P\left[H(S_{t+\tau})\right]$ |
|---|---|---|
| Panel A: Moments as in Neuberger (2012) | | |
| $2(\frac{S_{t+\tau}}{S_t}-1-\ln\frac{S_{t+\tau}}{S_t})$ | $H(S_t)=H'(S_t)=0$ <br> $H''(K)=\dfrac{2}{K^2}$ | $e^{r\tau}\int\limits_{S_t}^{\infty}\frac{2}{K^2}C^P(t,\tau,K)dK+e^{r\tau}\int\limits_{0}^{S_t}\frac{2}{K^2}P^P(t,\tau,K)dK$ |
| $6(2+\ln\frac{S_{t+\tau}}{S_t}-2\frac{S_{t+\tau}}{S_t}+\frac{S_{t+\tau}}{S_t}\ln\frac{S_{t+\tau}}{S_t})$ | $H(S_t)=H'(S_t)=0$ <br> $H''(K)=6(\dfrac{K-S_t}{S_tK^2})$ | $e^{r\tau}\int\limits_{S_t}^{\infty}6(\frac{K-S_t}{S_tK^2})C^P(t,\tau,K)dK+e^{r\tau}\int\limits_{0}^{S_t}6(\frac{K-S_t}{S_tK^2})P^P(t,\tau,K)dK$ |
| Panel B: Moments as in Bakshi, Kapadia, and Madan (2003) ($k\geq 2$) | | |
| $\left(\ln\frac{S_{t+\tau}}{S_t}\right)^k$ | $H(S_t)=H'(S_t)=0$ <br> $H''(K)=\dfrac{k(k-1)\left(\ln\frac{K}{S_t}\right)^{k-2}-k\left(\ln\frac{K}{S_t}\right)^{k-1}}{K^2}$ | $e^{r\tau}\int\limits_{S_t}^{\infty}\dfrac{k(k-1)\left(\ln\frac{K}{S_t}\right)^{k-2}-k\left(\ln\frac{K}{S_t}\right)^{k-1}}{K^2}C^P(t,\tau,K)dK$ <br> $+\,e^{r\tau}\int\limits_{0}^{S_t}\dfrac{k(k-1)\left(\ln\frac{K}{S_t}\right)^{k-2}-k\left(\ln\frac{K}{S_t}\right)^{k-1}}{K^2}P^P(t,\tau,K)dK$ |
| Panel C: Moments as in Christoffersen, Jacobs, and Chang (2012) ($k\geq 2$) | | |
| $\left(\frac{S_{t+\tau}-S_t}{S_t}\right)^k$ | $H(S_t)=H'(S_t)=0$ <br> $H''(K)=\dfrac{k(k-1)}{S_t^2}\left(\dfrac{K-S_t}{S_t}\right)^{k-2}$ | $e^{r\tau}\int\limits_{S_t}^{\infty}\dfrac{k(k-1)}{S_t^2}\left(\dfrac{K-S_t}{S_t}\right)^{k-2}C^P(t,\tau,K)dK$ <br> $+\,e^{r\tau}\int\limits_{0}^{S_t}\dfrac{k(k-1)}{S_t^2}\left(\dfrac{K-S_t}{S_t}\right)^{k-2}P^P(t,\tau,K)dK$ |

This table shows how different moments of the return distribution under the physical measure can be expressed in terms of the current price $S_t$, the risk-free interest rate $r$, current option prices, and the utility function of the representative investor. $C^P(t,\tau,K)$ and $P^P(t,\tau,K)$ denote the expected discounted payoffs of call and put options, respectively, under the physical measure, as given in Proposition 1. They are functions of current option prices and the utility function. The table has three panels. Panel A considers the variance and skewness measures studied by Neuberger (2012) (see Kozhan, Neuberger, and Schneider (2013) for the risk-neutral counterparts $E^Q\left[H(S_{t+\tau})\right]$). Panel B considers log returns (see Bakshi, Kapadia, and Madan (2003) for the risk-neutral counterparts) and Panel C discrete returns (see Christoffersen, Jacobs, and Chang (2012) for the risk-neutral counterparts).

**Table 2:** Descriptive Statistics of the Physical Variance and Skewness for Different Levels of Risk Aversion.

**Panel A: Variance (x 100)**

| | Mean | Std. Dev. | Q3 | Median | Q1 |
|---|---|---|---|---|---|
| Risk Neutral | 0.464 | 0.437 | 0.548 | 0.346 | 0.231 |
| RRA=1 | 0.404 | 0.359 | 0.489 | 0.300 | 0.206 |
| RRA=2 | 0.391 | 0.376 | 0.454 | 0.278 | 0.187 |
| RRA=3 | 0.423 | 0.524 | 0.451 | 0.275 | 0.181 |
| RRA=4 | 0.519 | 0.929 | 0.478 | 0.277 | 0.173 |
| RRA=5 | 0.723 | 1.840 | 0.514 | 0.298 | 0.182 |

**Panel B: Skewness**

| | Mean | Std. Dev. | Q3 | Median | Q1 |
|---|---|---|---|---|---|
| Risk Neutral | -1.845 | 0.752 | -1.302 | -1.769 | -2.269 |
| RRA=1 | -0.992 | 0.874 | -0.539 | -1.115 | -1.600 |
| RRA=2 | -0.125 | 1.227 | 0.395 | -0.459 | -0.932 |
| RRA=3 | 0.612 | 1.430 | 1.251 | 0.142 | -0.310 |
| RRA=3 | 1.167 | 1.437 | 1.956 | 0.740 | 0.160 |
| RRA=5 | 1.555 | 1.345 | 2.399 | 1.223 | 0.557 |

This table shows descriptive statistics of the ex-ante physical return variance (Panel A) and skewness (Panel B) of the S&P500 index for different levels of risk aversion. The data period is January 1996 to December 2011 and delivers 192 monthly observations. Moments were calculated according to the formulas from Panel A of Table 1 under the assumption of a representative investor with CRRA utility. The coefficient of relative risk aversion (RRA) takes values between 0 (Risk Neutral) and 5.

**Table 3:** Results of Empirical Analyses.

**Panel A: Variance Risk Premium**

| | Mean | Std. Dev. | Q3 | Median | Q1 |
|---|---|---|---|---|---|
| Realized x 100 | 0.365 | 0.605 | 0.373 | 0.199 | 0.111 |
| Risk Neutral x 100 | 0.464 | 0.437 | 0.548 | 0.346 | 0.231 |
| (Realized - Risk Neutral) x 100 | -0.099 | 0.463 | -0.042 | -0.122 | -0.212 |
| Physical x 100 | 0.361 | 0.346 | 0.422 | 0.259 | 0.161 |
| (Realized - Physical) x 100 | 0.004 | 0.470 | 0.012 | -0.053 | -0.123 |

**Panel B: Forward Looking Market Risk Premium**

| | Mean | Std. Dev. | Q3 | Median | Q1 |
|---|---|---|---|---|---|
| Relative Risk Aversion ($\gamma$) | 3.891 | 2.161 | 5.250 | 3.750 | 2.000 |
| Market Risk Premium x 100 | 1.150 | 0.899 | 1.471 | 1.014 | 0.543 |

**Panel C: Skewness Risk Premium**

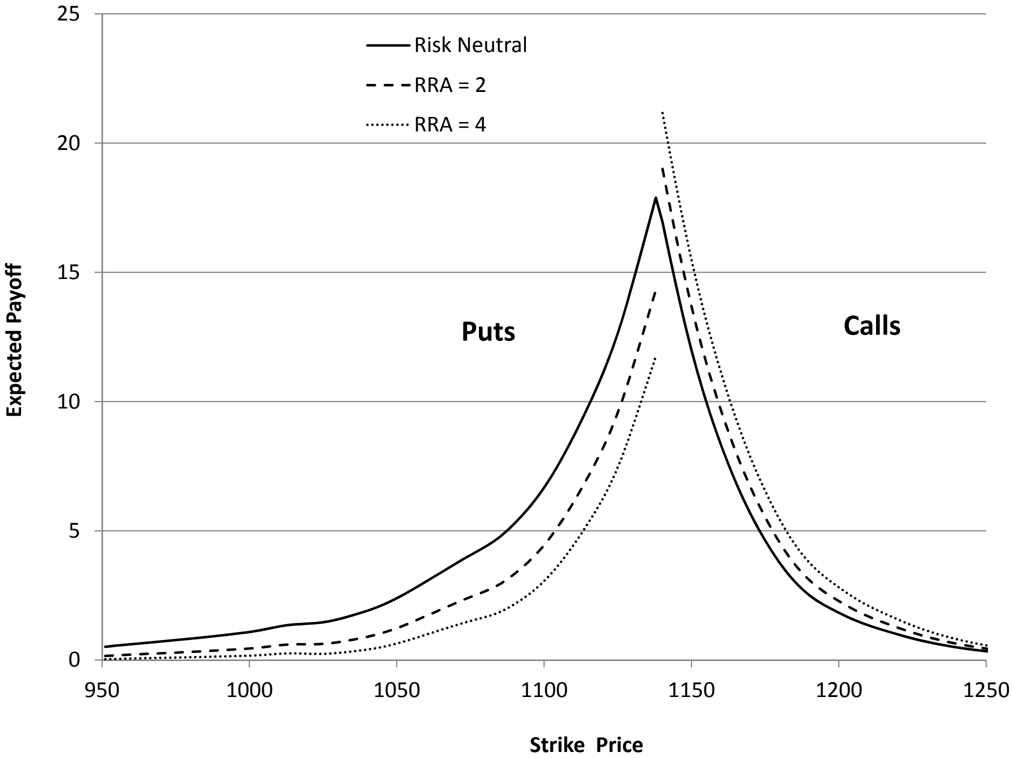
| | Mean | Std. Dev. | Q3 | Median | Q1 |
|---|---|---|---|---|---|
| Realized | -1.137 | 0.573 | -0.725 | -1.110 | -1.427 |
| Risk Neutral | -1.845 | 0.752 | -1.302 | -1.769 | -2.269 |
| (Realized - Risk Neutral) | 0.708 | 0.771 | 1.107 | 0.603 | 0.227 |
| Physical | 0.584 | 0.393 | 0.744 | 0.506 | 0.331 |
| (Realized - Physical) | -1.722 | 0.727 | -1.196 | -1.645 | -2.201 |

**Panel D: Implied Disappointment Aversion**

| | Mean | Std. Dev. | Q3 | Median | Q1 |
|---|---|---|---|---|---|
| Relative Risk Aversion ($\gamma$) | 0.500 | 0.417 | 0.200 | 0.400 | 0.700 |
| Disappointment Aversion ($A$) | 0.859 | 0.127 | 0.775 | 0.875 | 0.975 |

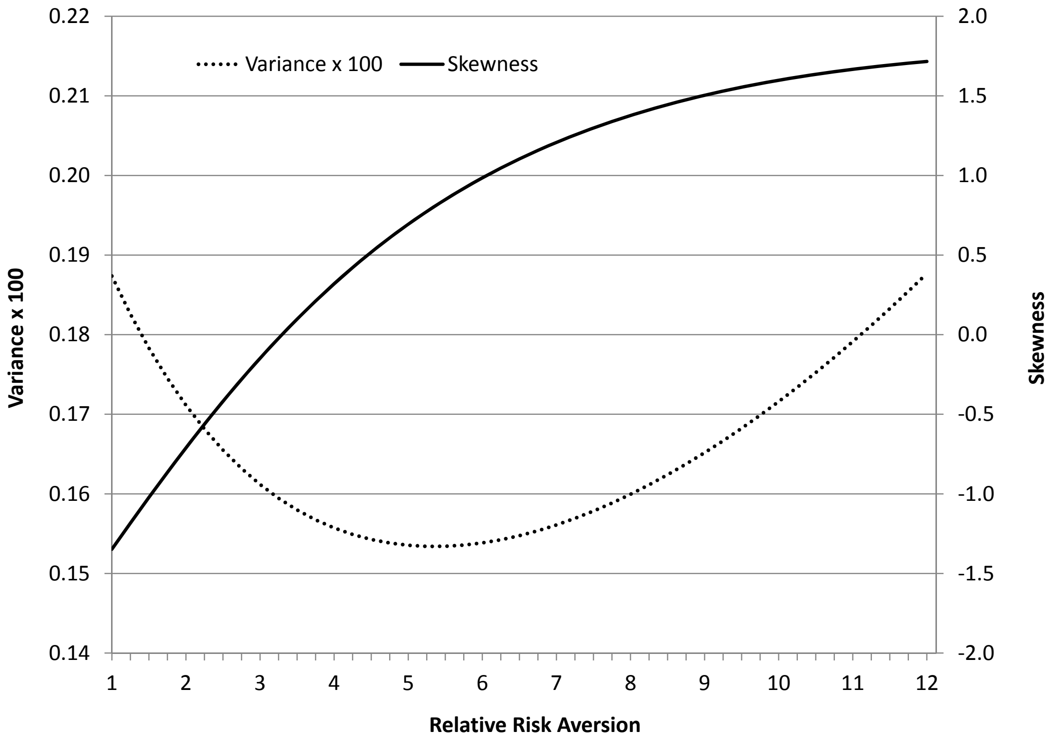
This table shows the results of different empirical analyses. All results are based on monthly data over the period from January 1996 to December 2011. The descriptive statistics refer to 192 observations for Panels A, B, and C, and 181 observations for Panel D. Panel A shows descriptive statistics for the risk-neutral variance, the ex-ante physical variance, and the realized variance. The physical variance uses the model of a representative investor with CRRA utility and time-varying $\gamma$, which is obtained by minimizing the variance. Panel B shows descriptive statics for these time-varying $\gamma$s and the corresponding forward-looking market risk premiums. Panel C provides descriptive statistics for the risk-neutral skewness, the ex-ante physical skewness, and the realized skewness. The relative risk aversion of the representative investor is the same as used for the results in Panel A. Finally, Panel D provides descriptive statistics for implied estimates of the preference parameters $\gamma$ and $A$ in a model of a representative investor with disappointment aversion. The estimates are obtained by selecting the parameter combination that leads to an average skewness risk premium closest to zero over a rolling estimation window of 12 months.

**Figure 1:** Effects of Risk Aversion on the Expected Payoffs of Call and Put Options Under the Physical Measure.



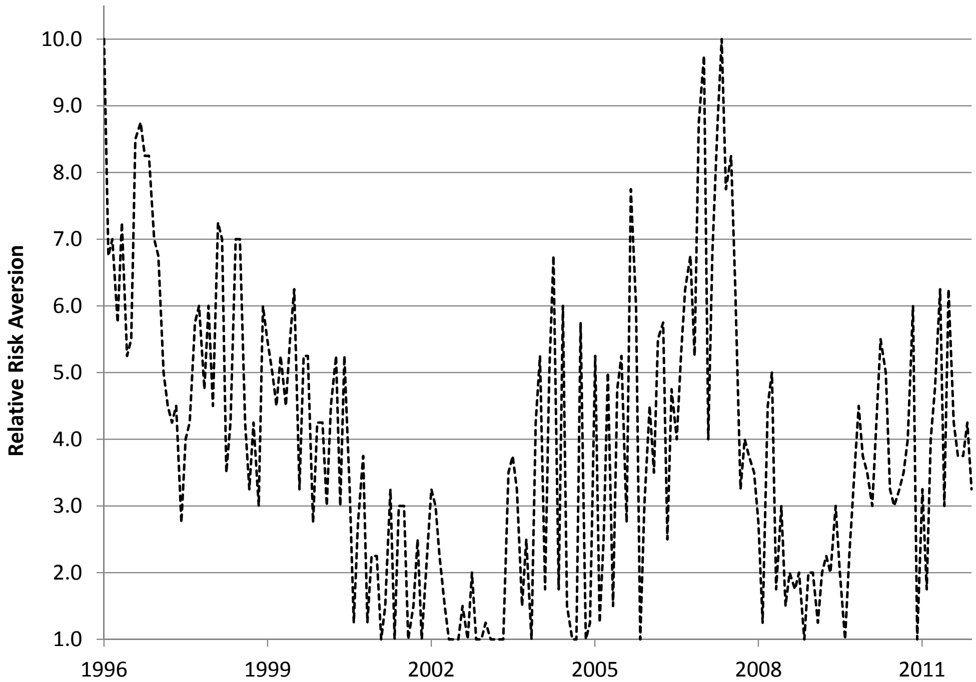

This figure shows the expected payoffs of at-the-money and out-of-the-money call and put options for different strike prices and different levels of risk aversion. Values are based on the spot and derivatives prices for the S&P500 index on 20/01/2004 and use the formulas from Equations (4) and (5). The forward price on that date was 1138.23. Expected payoffs are calculated under the assumption of a representative investor with CRRA utility. The solid line depicts the benchmark case of a risk-neutral representative investor. The dashed line refers to an investor with relative risk aversion of 2, the dotted line to one with a relative risk aversion of 4. The expected payoffs of calls are presented on the right hand side of the figure (strike prices above forward price), the expected payoffs of puts are given on the left hand side of the figure (strike prices below forward price).

**Figure 2:** Effects of Risk Aversion on the Physical Variance and Skewness.



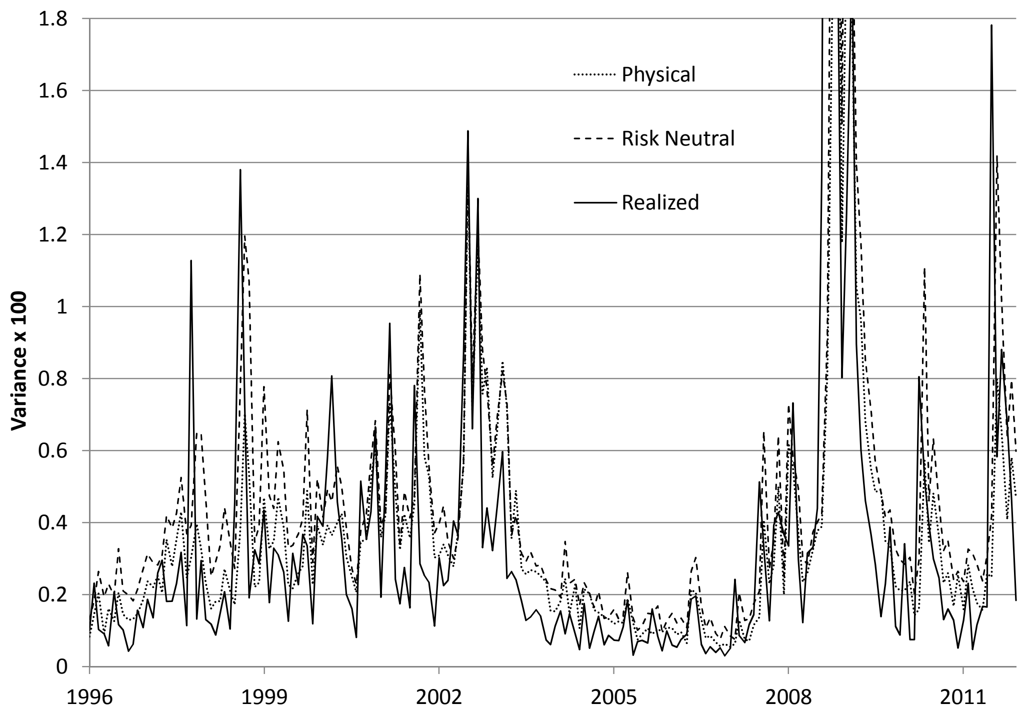

This figure shows the ex-ante variance and skewness under the physical measure for different levels of risk aversion of the representative investor. Values are based on spot and derivatives prices for the S&P500 index on 20/01/2004 and use the formulas from Panel A of Table 1. The representative investor has CRRA utility with varying levels of the coefficients of relative risk aversions, ranging from 1 (log utility) to 12. The dotted line shows the variance multiplied by 100 and the solid line shows the skewness. The scale on the vertical axis on the left hand side of the figure refer to variance and the one on the right hand side of the figure to skewness.

**Figure 3:** Implied Coefficient of Relative Risk Aversion Over Time.



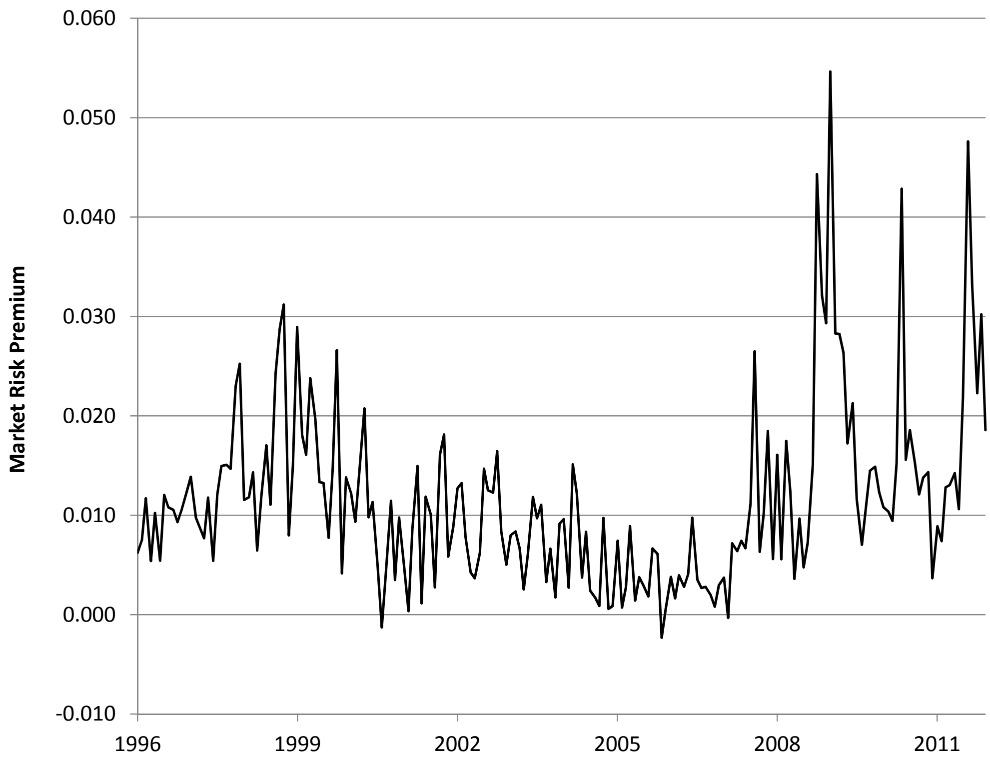

This figure shows the the implied coefficient of relative risk aversion ($\gamma$) over the period from January 1996 to December 2011. The coefficients are obtained under the assumption of a representative investor with CRRA utility. For each month, the $\gamma$ value in the range $[1, 10]$ that minimizes the ex-ante physical variance is selected.

**Figure 4:** Realized, Risk-Neutral, and Physical Variance Over Time.



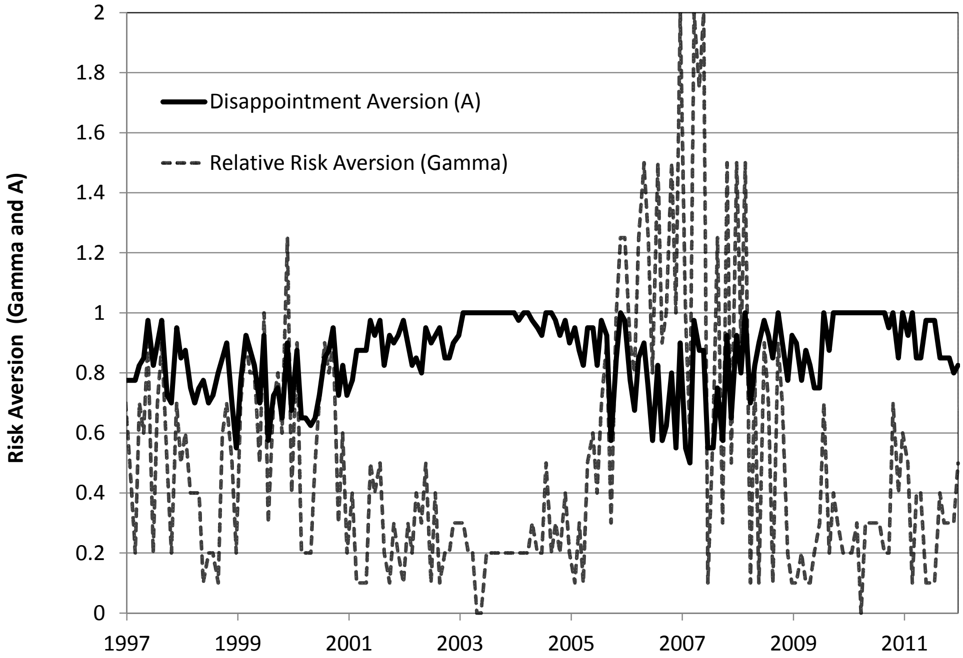

This figure shows the risk-neutral variance (dashed line), the ex-ante physical variance (dotted line) and the realized variance (solid line) over the period from January 1996 to December 2011.

**Figure 5:** Forward-Looking Market Risk Premium Over Time.




This figure shows the forward-looking monthly market risk premium over the period from January 1996 to December 2011. The values are obtained under the assumption of a representative investor with CRRA utility and a time-varying coefficient of relative risk aversion ($\gamma$). The $\gamma$ values are the ones shown in Figure 3.

**Figure 6:** Implied Risk Aversion and Disappointment Aversion.




This figure shows the implied coefficients of risk aversion ($\gamma$) and disappointment aversion ($A$) for the period January 1997 to December 2011. The estimates are obtained by selecting the parameter combination that leads to an average skewness risk premium closest to zero over a rolling estimation window of 12 months for a representative investor with a utility function according to Equation 15.

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