CENTRAL BANK POLICY ANNOUNCEMENT AND CHANGES IN INVESTMENT BEHAVIOR: EVIDENCE FROM MICRO DATA IN BOND FUTURES MARKETS*

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Abstract

This paper presents a theoretical model to explain how financial traders incorporate public and private information into security prices and proposes an empirical framework to identify surprises happening in financial markets. We apply the model to the tick-by-tick data on bond futures prices and show that the Bank of Japan's introduction of quantitative and qualitative monetary easing was one of the biggest surprises that happened during the period of 2005 through 2016. The analysis also shows that the sensitivity of bond futures markets to the Bank's announcements has strengthened since the introduction of negative interest rate policy. In contrast, the sensitivity to economic indicators and surveys has weakened substantially.

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1. INTRODUCTION

Since 1990s the Bank of Japan (BOJ) has introduced innovative monetary policies to achieve economic and financial stability in Japan. Particularly since 2013, under the command of Governor Kuroda, the BOJ made four large policy changes to combat with long-lasting deflation and to raise inflation rates to its target rate of two percent: quantitative and qualitative monetary easing in 2013; its enlargement in 2014; negative interest rate policy and yield curve control in 2016.[1] A common strategy taken in these policies is to lower and stabilize bond yields, particularly those on long-term bonds, around an appropriate level through various policy measures, such as large-scale purchases of government bonds. These policies had a substantial impact on financial markets.[2] In particular, the impact of the introduction of quantitative and qualitative monetary easing was so large that the circuit breakers were triggered twice in the bond futures market on April 5, 2013.

The central bank's controllability of bond yields depends on its skills to communicate with market participants. Good communication is an essential part of good monetary policy. Particularly in recent years, with interest rates very low, central banks in advanced countries give a substantial role to communication tools, such as forward guidance (see, e.g., Blinder, et al., 2008). A lack of communication is often a cause of surprises in financial markets. In the standard macroeconomics, surprises are thought of as something central banks should avoid. Surprises do damage to the credibility of the central bank. Without credibility, markets do not respond to the announcements of the central bank as it expected. Surprises, however, are sometimes unavoidable, particularly when the central bank introduces innovative policy measures. Even in that case, the central bank should take an appropriate communication strategy that enables market participants to understand the central bank's policy intention correctly and quickly.

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[1] See Bank of Japan (2013, 2014, 2016a, 2016b) for the related statements.

[2] The impact of quantitative and qualitative monetary easing in 2013 on ten-year government cash bond yields was not so large as that of the *unyobu shock* in 1998 and the *VaR shock* in 2003.

This paper presents an analytical framework to identify and quantify surprises happening in financial markets. For this purpose, we exploit Kamada and Miura's (2014) bond market model. One of the notable features of their model is its double-layered structure of information, consisting of public and private information. Private information differs from public information. Anyone can access freely to public information, but not to private information. To make profits, traders want to predict the impact of public information before it is released. For that purpose, they gather private information and take a position based on it. This makes asset prices to rise and fall before public information is released in the future. In the model, the volatility of asset prices reflects (i) traders' expected impact of public information on asset prices and (ii) the usefulness of private information to predict the impact of public information. Once public information is released, asset prices are adjusted to it. Surprises happen if asset prices go beyond traders' expectations.

We use market micro data to identify and quantify surprises that happened in financial markets. New information—policy announcements, economic data, various surveys, economic reports written by influential economists, and all kinds of rumors—is coming every second, and sometimes even every millisecond. Some information is irrelevant for trading purposes, but some has long-lasting effects on asset prices. Daily or more infrequent data are sometimes not so informative as to capture psychological subtlety in each market. For this reason, we use tick-by-tick data in financial markets. Government bond markets are particularly important for us to see how traders' response to the BOJ's policy announcements has changed recently. We have a particular interest in the following question: Is there any behavioral change observed in bond futures markets after the introduction of new policy measures?

The remainder of this paper is organized as follows. Section 2 presents a theoretical model to capture surprises in financial markets and conducts simulations to demonstrate the characteristics of the model. Section 3 proposes an empirical strategy used to identify traders' surprises in the micro data on bond futures prices and discusses how market behavior has changed since the BOJ's introduction of new monetary policy measures. Section 4 concludes.

2. THE MODEL

2.1. Public and private information in financial markets

Nirei, et al. (2013) have created a model to describe herding behavior in stock markets.[3] Their model has two ingredients: (i) traders gather private information on future stock prices before making investment decisions; (ii) traders make inferences on other traders' private information based on their observations of stock prices. When traders see stock prices going up, they infer that someone gets information which indicates that stock prices will rise in the future. This inference creates additional demand for stocks and pushes up stock prices further. When stock prices are falling down, traders make an opposite inference and sell stocks, with the result of further declines in stock prices. Due to this herding behavior among traders, stock prices become volatile and fat-tail distributions are created.

The model of Nirei, et al. (2013), however, has a drawback: it deals only with private information, not with public information. All traders have equal access to public information, but only limited traders are allowed to access to private information. The empirical literature on market microstructure shows that public information has a strong impact on price formation, especially in bond markets (see, e.g., Fleming and Remolona, 1997, 1999).[4] Public information includes not only statistics that have a direct impact on asset prices, such as inflation expectations, the potential rate of growth, overseas interest rates, etc., but also a wide range of other types of information that affect asset prices indirectly, such as labor statistics and economic surveys.

Public information of particular importance is central bank policy

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[3] A variety of herding models have been proposed to express the behavior in financial markets (e.g., Banerjee, 1992).

[4] Stock prices are considered to be determined mostly by private information, such as unconfirmed information about the development of new products and changes in management strategy. In contrast, little evidence has been provided that public information has significant effects on stock markets. See Cutler, et al. (1989) for related studies.

announcements and associated speeches by bank executives. As witnessed in Japan, the BOJ's policy announcements since April 2013 have had a substantial impact on price formation in bond markets. To analyze the impact of central bank announcements, Kamada and Miura (2014) introduced a double-layered structure of information, consisting of both public and private information. Below we slightly modify their model to exploit rich information contained in the tick-by-tick data we use for empirical studies in Section 3.

2.2. The structure of traders' subjective probability

There are two financial states, H and L. We denote the corresponding asset prices by p_H and p_L ($< p_H$), respectively. State H is a high-price state or a low-interest state; state L is a low-price state or a high-interest state. Traders do not know which state they live in, but have a subjective probability distribution about it.

Suppose that the τ-th public information is released. Traders believe that they are in state H with probability π_τ and state L with probability $1 - \pi_\tau$. The fair price of the asset is given by

$$p_\tau = \pi_\tau p_H + (1 - \pi_\tau) p_L \,. \tag{1}$$

Denote the likelihood ratio of state L over H by $\theta_\tau \equiv (1 - \pi_\tau)/\pi_\tau$. Then, the fair price is alternatively rewritten as

$$p_\tau = p_L + \frac{p_H - p_L}{1 + \theta_\tau} \,. \tag{2}$$

In the special case of $\pi_\tau = 0.5$, or $\theta_\tau = 1$, traders are completely uncertain about financial states. We assume that π_τ and θ_τ are common parameters across traders.

There are two types of information, *public* and *private*. Public information may not convey correct information about financial states.[5] Thus, traders remain uncertain

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[5] Unambiguity and readability are different things. A readable statement is not always unambiguous. The BOJ's statement regarding the introduction of quantitative and qualitative monetary easing is a good example. The policy is aimed at the target inflation rate of two percent in around two years. The statement was readable, but confusing to the

about financial states even after public information is released. Public information is correct with probability q_τ (> 0.5) and wrong with probability $1 - q_\tau$. The role of q_τ is discussed in detail below. Here, we point out that the size of q_τ is related to the *plausibility* of public information and its *relevance* to financial states. No matter how precise, public information has no value if it has nothing to do with asset prices; no matter how relevant to asset prices, it has no value if completely wrong. We assume that q_τ is common to all traders.[6]

By private information, we mean unpublicized information that traders gather to predict future public information. Denote trader i's private information by $x_{i\tau}$. He knows that $x_{i\tau}$ is *likely* to be generated from distribution F_H in state *H* or F_L in state *L*. Denote the associated densities by f_H and f_L, respectively. The likelihood ratio, $\delta(x) \equiv f_H(x)/f_L(x)$, is assumed monotonically decreasing in x. This assumption allows traders to make the following conjecture: If x is high, it is likely that they are in state *H*.

Traders' expectations about public information may differ from actual public information released later. Divide traders into two groups: those on the *long side* and those on the *short side*. Traders on the long side believe that if they are in state *H*, private information is generated from F_H with probability $q_{a\tau}$ (> 0.5) and from F_L with probability $1 - q_{a\tau}$; if they are in state *L*, it is from F_H with probability $1 - q_{a\tau}$ and from F_L with probability $q_{a\tau}$. Note that $q_{a\tau}$ is not necessarily equal to q_τ introduced above. For traders on the short side, the corresponding probability is given by $q_{b\tau}$ (> 0.5), which is not necessarily equal to $q_{a\tau}$ nor to q_τ. We assume that $q_{a\tau}$ and $q_{b\tau}$ are common to all traders.

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majority of traders. Following the Fisher equation, high inflation implies high nominal interest. Thus, traders took the statement as a signal of the Bank allowing long-term interest rates to rise. But the Bank's intention is that it purchases assets in a large scale to squeeze the term premium more than to raise inflation expectations, thereby lowering long-term interest rates (Kamada, 2014).

[6] Whether these assumptions are realistic or not is a matter of debate. Considering this issue further is beyond the scope of this study. Interested readers are recommended to consult with Keynes (1921) and Keynes's reply to the criticism by Frank P. Ramsey (Keynes, 1933).

2.3. *Informed traders on the long side*

Two types of traders are playing in markets, *informed and uninformed*. Informed traders gather private information, but uninformed traders do not. As already mentioned, informed traders are divided further into two groups: *long-side* and *short-side* traders.[7] Long-side traders choose between buying assets or doing nothing, while short-side traders choose between selling assets or doing nothing.

Let us begin with long-side traders. Trader i updates his subjective probability, using the asset price observed in the market as well as private information, $x_{i\tau}$, he collected. Denote the total number of long-side informed traders by n_a, of which k traders are ready to buy the asset, while the remaining $n_a - k$ do nothing. If traders buy the asset, they do so at an ask price, $p_{a\tau}(k)$, offered by uninformed traders. We assume that $p_{a\tau}(k)$ is an increasing function of k. Long-side informed traders know this function. Therefore, when the asset price is offered, traders infer how many long-side informed traders are ready to buy the asset.

Traders use Bayes' rule to update the prior likelihood ratio, $\theta_{\tau-1}$. Denote trader i's posterior probability of state H and L by $\pi_{ai\tau}$ and $1-\pi_{ai\tau}$, respectively. Denote the posterior likelihood ratio of state L over H by $\theta_{ai\tau} \equiv (1-\pi_{ai\tau})/\pi_{ai\tau}$. Trader i uses information set $\{x_{i\tau}, p_{a\tau}(k)\}$ to calculate $\theta_{ai\tau}$ as follows.

$$\theta_{ai\tau}(x_{i\tau}, p_{a\tau}(k)) = \frac{\Pr(L|x_{i\tau}, p_{a\tau}(k))}{\Pr(H|x_{i\tau}, p_{a\tau}(k))} = \frac{\Pr(x_{i\tau}, p_{a\tau}(k)|L)}{\Pr(x_{i\tau}, p_{a\tau}(k)|H)}\theta_{\tau-1}\,. \tag{3}$$

Define a critical value, $\bar{x}_\tau(k)$, such that when $p_{a\tau}(k)$ is offered, a trader buys the asset if his private information $x_{i\tau}$ is greater than or equal to it, but otherwise does nothing.

The decision rule for long-side informed traders

$$x_{i\tau}\begin{cases} \geq \bar{x}_\tau(k) & \Rightarrow \quad Buy\ the\ asset\,; \\ < \bar{x}_\tau(k) & \Rightarrow \quad Opt\ out\,. \end{cases}$$

When an ask price $p_{a\tau}(k)$ is offered by uninformed traders, an informed

[7] Nirei, et al. (2013) considers only long-side informed traders, while we consider both long side and short side.

trader infers that there are $k-1$ traders ready to buy the asset except for him and the remaining $n_a - k$ do nothing. Therefore, depending on financial states, the probability of $\{x_{i\tau}, p_{a\tau}(k)\}$ being generated is given as follows.

$$\Pr(x_{i\tau}, p_{a\tau}(k)|L) = q_{a\tau}F_L\big(\bar{x}_\tau(k)\big)^{n_a-k}(1-F_L(\bar{x}_\tau(k)))^{k-1}f_L(x_{i\tau}) \\ +(1-q_{a\tau})F_H\big(\bar{x}_\tau(k)\big)^{n_a-k}(1-F_H(\bar{x}_\tau(k)))^{k-1}f_H(x_{i\tau})\,; \tag{4}$$

$$\Pr(x_{i\tau}, p_{a\tau}(k)|H) = (1-q_{a\tau})F_L\big(\bar{x}_\tau(k)\big)^{n_a-k}(1-F_L(\bar{x}_\tau(k)))^{k-1}f_L(x_{i\tau}) \\ +q_{a\tau}F_H\big(\bar{x}_\tau(k)\big)^{n_a-k}(1-F_H(\bar{x}_\tau(k)))^{k-1}f_H(x_{i\tau})\,. \tag{5}$$

Substituting these equations into equation (3) gives

$$\theta_{ai\tau}(x_{i\tau}, p_{a\tau}(k)) = \frac{q_{a\tau}A\big(\bar{x}_\tau(k)\big)^{n_a-k}B\big(\bar{x}_\tau(k)\big)^{k-1}\delta(x_{i\tau}) + 1 - q_{a\tau}}{(1-q_{a\tau})A\big(\bar{x}_\tau(k)\big)^{n_a-k}B\big(\bar{x}_\tau(k)\big)^{k-1}\delta(x_{i\tau}) + q_{a\tau}}\theta_{\tau-1}\,, \tag{6}$$

where $A(x) \equiv F_L(x)/F_H(x)$ and $B(x) \equiv (1-F_L(x))/(1-F_H(x))$. Since $\delta(x)$ is decreasing in x, inequalities $A(x) > \delta(x) > B(x)$ holds. In addition, $A(x)$, $\delta(x)$, and $B(x)$ are all decreasing in x (Nirei, et al., 2013).

To close the model, we need to solve for the critical value, $\bar{x}_\tau(k)$. Assume that long-side informed traders are risk neutral. If asset prices are expected to rise, traders buy the asset now and sell it when prices rise actually. Trader i buys the asset if

$$\pi_{ai\tau}p_H + (1-\pi_{ai\tau})p_L \geq p_{a\tau} \tag{7}$$

$$\Leftrightarrow \quad \frac{p_H - p_{a\tau}}{p_{a\tau} - p_L} \geq \theta_{ai\tau}\,. \tag{8}$$

If $x_{i\tau} = \bar{x}_\tau(k)$, asset trading generates no profits by definition. Therefore, equations (6) and (8) hold simultaneously with equality through $\theta_{ai\tau}(\bar{x}_\tau(k), p_{a\tau}(k))$. That is,

$$\frac{p_H - p_{a\tau}(k)}{p_{a\tau}(k) - p_L} = \frac{q_{a\tau}A\big(\bar{x}_\tau(k)\big)^{n_a-k}B\big(\bar{x}_\tau(k)\big)^{k-1}\delta(\bar{x}_\tau(k)) + 1 - q_{a\tau}}{(1-q_{a\tau})A\big(\bar{x}_\tau(k)\big)^{n_a-k}B\big(\bar{x}_\tau(k)\big)^{k-1}\delta(\bar{x}_\tau(k)) + q_{a\tau}}\theta_{\tau-1}\,. \tag{9}$$

This yields $\bar{x}_\tau(k)$.

We can show that the decision rule for long-side traders is incentive compatible. Let $C_{ai\tau} \equiv A\big(\bar{x}_\tau(k)\big)^{n_a-k}B\big(\bar{x}_\tau(k)\big)^{k-1}\delta(x_{i\tau})$. Since $\delta(x_{i\tau})$ is decreasing in $x_{i\tau}$, $C_{ai\tau}$ is also decreasing in $x_{i\tau}$. With $q_{a\tau} > 0.5$, the right-hand side of equation (6) is increasing in $C_{ai\tau}$, and thus decreasing in $x_{i\tau}$. By definition, if trader i is ready to buy assets, $x_{i\tau} \geq \bar{x}_\tau(k)$ must hold. Thus, the right-hand side of equation (6) is smaller than that of equation (9), which satisfies inequality (8) and proves the incentive compatibility of the rule.

Now we can show that the total demand for the asset is an increasing function of the asset price. As shown in *Lemma 1* in the appendix, when n_a is sufficiently large, $\bar{x}_\tau(k)$ is a decreasing function of k, as drawn in Figure 1(a). Suppose that trader 1 has private information $x_{1\tau}$ in the figure. He buys one unit of the asset if the asset price is higher than or equal to $p_{a\tau}(3)$, but no assets otherwise. Suppose that trader 2 has private information $x_{2\tau}$. Trader 2 buys one unit of the asset if the asset price is higher than or equal to $p_{a\tau}(2)$. If there are only two informed traders on the long side, the total demand for the asset is given as an upward sloping curve, as shown in Figure 1(b). This property generates herding behavior among traders.

The upward-sloping demand function derived above contrasts with the usual downward-sloping demand function found in standard microeconomics text books. Let us consider the case where each trader uses nothing but his private information to make investment decisions. This is the same as assuming $A\left(\bar{x}_\tau(k)\right)^{n_a-k} B\left(\bar{x}_\tau(k)\right)^{k-1} = 1$ in equation (9). When the asset price goes up, the left-hand side of equation (9) falls. Since $\delta(x)$ is decreasing in x, $\bar{x}_\tau(k)$ must be increasing in k. In this case, the total demand function is drawn as a downward-slopping curve, as opposed to the upward-slopping demand function obtained in the case of herding market traders.

The equilibrium asset price and trading volume are determined as follows. Suppose that uninformed traders supply k units of the asset at the price of $p_{a\tau}(k)$. Each long-side informed trader compares his private information, $x_{i\tau}$, with critical value $\bar{x}_\tau(k)$. If the former is greater than or equal to the latter, he buys one unit of the asset. Otherwise, his demand is zero. The total demand is given by the sum of all long-side informed traders' demand, which is denoted by $D_{a\tau}(k)$. Equilibrium trading volume, which is denoted by k^*, must satisfy the equality $D_{a\tau}(k^*) = k^*$. When there are multiple k^*, the minimum k^* is chosen as a unique solution, as is in Nirei, et al. (2013). *Proposition 1* in the appendix shows the existence of such equilibrium.

2.4. Informed traders on the short side

A similar argument holds for informed traders on the short side. Suppose that there are n_b short-side informed traders. Let $p_{b\tau}(h)$ be a bid price offered by uninformed traders when h short-side informed traders are ready to sell the asset. Assume that the bid price function is decreasing in h. Define critical value $\underline{x}_\tau(h)$ such that each trader sells the asset if her private information is equal to or smaller than this critical value, but does not otherwise.

<u>*The decision rule for short-side informed traders*</u>

$$x_{j\tau}\begin{cases}\le \underline{x}_\tau(h) & \Rightarrow \quad Sell\ the\ asset\ ; \\ > \underline{x}_\tau(h) & \Rightarrow \quad Opt\ out\ .\end{cases}$$

When each short-side trader is offered a bid price, $p_{b\tau}(h)$, she infers that h traders beside her are ready to sell the assets and the remaining $n_b - h$ do nothing. The likelihood ratio of state L over H is calculated as follows:

$$\theta_{bj\tau}(x_{j\tau}, p_{b\tau}(h)) = \frac{q_{b\tau} A\left(\underline{x}_\tau(h)\right)^{h-1} B\left(\underline{x}_\tau(h)\right)^{n_b-h} \delta(x_{j\tau}) + 1 - q_{b\tau}}{(1-q_{b\tau}) A\left(\underline{x}_\tau(h)\right)^{h-1} B\left(\underline{x}_\tau(h)\right)^{n_b-h} \delta(x_{j\tau}) + q_{b\tau}} \theta_{\tau-1}\ , \tag{10}$$

Informed traders are assumed to be risk neutral. Thus, if the asset price is expected to go down, traders sell the asset and buy it back when the asset price falls actually. Trader j sells the asset, if

$$\pi_{bj\tau} p_H + (1-\pi_{bj\tau}) p_L \le p_{b\tau} \tag{11}$$

$$\Leftrightarrow \quad \frac{p_H - p_{b\tau}}{p_{b\tau} - p_L} \le \theta_{bj\tau}\ . \tag{12}$$

By definition, traders' profits are zero if $x_{j\tau} = \underline{x}_\tau(h)$. Thus, equations (10) and (12) hold simultaneously with equality through $\theta_{bj\tau}(\underline{x}_\tau(h), p_{b\tau}(h))$. That is,

$$\frac{p_H - p_{b\tau}(h)}{p_{b\tau}(h) - p_L} = \frac{q_{b\tau} A\left(\underline{x}_\tau(h)\right)^{h-1} B\left(\underline{x}_\tau(h)\right)^{n_b-h} \delta\left(\underline{x}_\tau(h)\right) + 1 - q_{b\tau}}{(1-q_{b\tau}) A\left(\underline{x}_\tau(h)\right)^{h-1} B\left(\underline{x}_\tau(h)\right)^{n_b-h} \delta\left(\underline{x}_\tau(h)\right) + q_{b\tau}} \theta_{\tau-1}\ . \tag{13}$$

This solves for $\underline{x}_\tau(h)$.

The incentive compatibility of the decision rule for short-side traders is easy to show. To do so, we notice that $\underline{x}_\tau(h)$ is increasing in h, when n_b is sufficiently large (see *Lemma 1* in the appendix). This is in contrast with $\overline{x}_\tau(k)$, which is decreasing in k. An equilibrium price is defined as follows. Denote the total supply from short-side informed traders at the price of $p_{b\tau}(h)$ by $S_{b\tau}(h)$. Suppose that uninformed traders demand h units of the asset. Equilibrium volume h^* must satisfy the equality $S_{b\tau}(h^*) = h^*$. When there exist multiple h^*, the minimum h^* is chosen as a unique solution. *Proposition 1* in the appendix shows the existence of such equilibrium.

2.5. Defining surprises

One of the novel features of the current model is that it enables us to quantify surprises happening in financial markets. Let us start with the long side. The right-hand side of equation (6) is increasing in $C_{ai\tau}$, which is defined above and takes any value between 0 and infinity. Therefore, we have $\theta_{ai\tau}(x_{i\tau}, p_{a\tau}(k)) \geq \eta_{a\tau}\theta_{\tau-1}$, where $\eta_{a\tau} \equiv (1 - q_{a\tau})/q_{a\tau}$. Combining this with inequality (8), we have $p_{a\tau} \leq \overline{p}_{a\tau}$, where $\overline{p}_{a\tau}$ is the upper bound of ask prices, defined as

$$\overline{p}_{a\tau} \equiv p_L + \frac{p_H - p_L}{1 + \eta_{a\tau}\theta_{\tau-1}}. \tag{14}$$

We say that surprises happen if the fair price is updated to satisfy the inequality $\overline{p}_{a\tau} < p_\tau$, when the τ-th public information is released.

Recall that we defined private information as the information used to predict public information. Therefore, once public information is released, the private information loses its value. This implies that all traders have the same posterior probability distribution. This setting differs from that in Nirei, et al. (2013), in which private information does not become obsolete but accumulates over time. Under their assumption, as time goes by, each trader's information structure becomes more and more complex. The assumption employed in this paper simplifies the model substantially.

A similar argument can be made on the short side. The right-hand side of equation (10) is increasing in $C_{bj\tau}$, which is defined above and takes any value between 0 and infinity. Therefore, we have $\theta_{bj\tau}(x_{j\tau}, p_{b\tau}(k)) \geq \eta_{b\tau}\theta_{\tau-1}$, where $\eta_{b\tau} \equiv q_{b\tau}/(1 -$

$q_{b\tau}$). Combining this with inequality (12), we have $\underline{p}_{b\tau} \leq p_{b\tau}$, where $\underline{p}_{b\tau}$ is the lower bound of bid prices, defined as

$$\underline{p}_{b\tau} \equiv p_L + \frac{p_H - p_L}{1 + \eta_{b\tau}\theta_{\tau-1}}. \tag{15}$$

We say that surprises happen if the fair price is updated to satisfy the inequality $p_\tau < \underline{p}_{b\tau}$, when the τ-th public information is released.

The following definition of surprises is equivalent to that given above, but simplifies the empirical treatments significantly in a later section. Let $\eta_\tau \equiv \theta_\tau/\theta_{\tau-1}$. We call η_τ the *marginal value of public information* in this paper. Similarly, $\eta_{a\tau}$ and $\eta_{b\tau}$ are called traders' expected *marginal value of public information on the long and short sides*, respectively, and are not necessarily equal to η_τ. These marginal values of information correspond one-to-one to the asset prices of p_τ, $\overline{p}_{a\tau}$, and $\underline{p}_{b\tau}$ through equations (2), (14), and (15). We can alternatively define surprises in terms of these marginal values, as in the following table.

	Surprise	*No surprise*
Price base	$p_\tau < \underline{p}_{b\tau}$ *or* $\overline{p}_{a\tau} < p_\tau$	$p_\tau \leq \overline{p}_{a\tau} \leq p_\tau$
Information value base	$\eta_\tau < \eta_{a\tau}$ *or* $\eta_{b\tau} < \eta_\tau$	$\eta_{a\tau} \leq \eta_\tau \leq \eta_{b\tau}$

2.6. Uninformed traders' ask and bid price functions

So far, we have not explicitly described uninformed traders' ask and bid price functions. To conduct simulation analysis, however, we have to define them explicitly.

$$p_{a\tau}(k) = p_{\tau-1} + \phi_{a\tau}\left(\frac{k}{n_a}\right)^{\gamma_a} \quad for \ \ 0 \leq k \leq n_a\,; \tag{16}$$

$$p_{b\tau}(h) = p_{\tau-1} - \phi_{b\tau}\left(\frac{h}{n_b}\right)^{\gamma_b} \quad for \ \ 0 \leq h \leq n_b\,, \tag{17}$$

where $p_{\tau-1}$ is the fair price; and ϕ_a and ϕ_b are defined as follows:

$$\phi_{a\tau} \equiv \lambda_a\left(\frac{1}{1+\eta_{a\tau}\theta_{\tau-1}} - \frac{1}{1+\theta_{\tau-1}}\right)(p_H - p_L)\,; \tag{18}$$

$$\phi_{b\tau} \equiv \lambda_b \left(\frac{1}{1+\theta_{\tau-1}} - \frac{1}{1+\eta_{b\tau}\theta_{\tau-1}} \right) (p_H - p_L) \,, \tag{19}$$

where γ_a and γ_b are price elasticity. We assume $\gamma_a = \gamma_b = 0.5$, following the preceding studies (e.g., Lillo et al., 2003).[8]

We set the parameters so that the motion range of ask and bid prices offered by uninformed traders coincides with the range of prices acceptable by informed traders. We see first that $p_{a\tau}(0) = p_{b\tau}(0) = p_{\tau-1}$. Uninformed traders can offer an ask price higher than the fair price, but should not offer an ask price lower than the fair price. If an ask price is lower than the fair price, informed traders can gain from buying the asset at the ask price and immediately selling it at the fair price, even when they have no new information received. For a similar reason, uninformed traders can choose a bid price lower than the fair price, but should not set a bid price higher than the fair price.

Second, with $\lambda_a = 1$, we see $p_{a\tau}(1) = \overline{p}_{a\tau}$, the right hand side of which is the upper bound of an ask price that informed traders can accept.[9] Uninformed traders can choose any ask price higher than the upper bound. In that case, however, all traders stay out of the market waiting for a decline in ask prices. Similarly, with $\lambda_b = 1$, we see $p_{b\tau}(1) = \underline{p}_{b\tau}$, the right hand side of which is the lower bound of a bid price that informed traders can accept.

[8] The market liquidity is determined not only by λ_a and λ_b but also by γ_a and γ_b. Gabaix, et al. (2006) show that the cost of restoring inventories to their initial level depends on market liquidity and theoretically derive an ask price function that is similar to equation (16) when uninformed traders are risk-averse. However, when considering market liquidity, it is sufficient to examine only the role of λ_a and λ_b and take γ_a and γ_b as constant.

[9] This study assumes $0 \le \lambda_a, \lambda_b \le 1$ so that $\bar{x}_\tau(k)$ and $\underline{x}_\tau(h)$ become interior solutions. This is not a necessary condition for the analysis here. We can alternatively assume $\lambda_a, \lambda_b \ge 1$ and define the ask price as the smaller of the following two values: the price indicated by equation (16) and the upper-bound defined by equation (14). Similarly, we can define the bid price as the larger of the following two values: the price indicated by equation (17) and the lower-bound defined by equation (15).

2.7. Simulation analysis

Nirei, et al. (2013) built up a model to describe the herding behavior observed in security markets and show that the model generates a fat-tail distribution of asset prices theoretically. The current model is an extension of their model and thus thought of as inheriting its main characteristics. Below we conduct several simulations to show that this conjecture is right. We are particularly interested in whether the distribution of asset prices generated by the current model is indeed characterized by fat tails. We are also interested in under what conditions the tails of the distribution become fatter.

First, we show that the fat-tail asset-price distribution is generated by the current model. Assume that F_H and F_L are normal distributions with means μ_H and μ_L $(< \mu_H)$, respectively, and common standard deviation σ. Below, the following parameter set is used as a benchmark: $p_H = 100$, $p_L = 86$; $\mu_H = 1$, $\mu_L = -1$; $\sigma = 200$; $n_{a\tau} = n_{b\tau} = 10000$; $\theta_{\tau-1} = 1$; $q_{a\tau} = q_{b\tau} = 0.8$ (or $\eta_{a\tau} = 1/4$, $\eta_{b\tau} = 4$); $\lambda_{a\tau} = \lambda_{b\tau} = 0.8$. Below, private information is always generated from distribution F_H. The simulation is iterated 25000 times for each of the long and short sides. The result is presented in Figure 2, the horizontal axis indicates percent changes in prices, while the vertical axis does relative frequency. Compared with a normal distribution, the simulated distribution clearly shows fat tails.[10]

Next, we make comparative statics to see under what conditions the tails of the price distribution become fatter. We replace values in each of the parameters and simulate the distribution of asset prices. The results are shown in Figure 3. We see that the distribution becomes more fat-tailed, (i) when traders become more uncertain about the current financial state (i.e., $\theta_{\tau-1}$ is close to 1); (ii) when traders expect future public information to be more valuable (i.e., $q_{a\tau}$ and $q_{b\tau}$ are high); (iii) when traders receive more valuable private information to infer the marginal value of future public information (i.e., $\mu_H - \mu_L$ is large; σ is small).

Interesting results are obtained regarding λ_a and λ_b, the parameters of

[10] Note that the distribution in Figure 2 is skewed toward the right. This is because private information is generated from F_H.

market liquidity. Uninformed traders, when selling the assets to informed traders, infer that it becomes costly to restore their initial inventory levels, as the assets become scarce in the market. This implies that as market liquidity increases, λ_a and λ_b decrease. However, as shown in Figure 3(e), a decrease in λ_a and λ_b does not necessarily weaken the volatility of the asset price. One interpretation is as follows. As market liquidity increases, uninformed traders offer informed traders more favorable prices, which attract more informed traders into the market. This boosts up the demand for the asset and makes the asset price more volatile. The effects of market liquidity on asset price volatility depend on which of these two forces is stronger than the other.

3. EMPIRICAL ANALYSIS

3.1. Data

Tick-by-tick price data are indispensable to our empirical analysis of traders' psychological movements in response to new information arriving at every moment, especially, the BOJ's policy announcements. We herein focus on the Japanese government bond futures market, because policy announcements expectedly have the most straightforward impact on it among the markets in which such tick-by-tick data are available. Specifically, we utilize the "NEEDS" database provided by Nikkei Inc.[11] This database contains historical tick-by-tick transaction records of the Japanese government bond futures listed currently on the Osaka Exchange and on the Tokyo Stock Exchange prior to March 24, 2014.

Our dataset is constructed from the "NEEDS" database as follows. First of all, we consider only prices of market orders. This is not only for simplicity but also because a market order generally reflects traders' intentions to buy or sell more clearly than a limit order. We emphasize that prices are recorded in a distinguishable manner between ask prices and bid prices, which is critical to implementing the empirical

[11] Nikkei Inc., "NEEDS," is a data source of Table 1 and Figures 5 to 19, 21, and 22.

strategy described below. In addition, we exclude futures contracts other than those on 10-year bonds with the most actively traded contract month, i.e., the nearest contract month. We also exclude mini 10-year bond futures. Transaction volume of these miscellaneous contracts is relatively limited. On the other hand, given that information coming from overseas is far from negligible, we incorporate market orders during both the day session and the night session[12]. Finally, our sample period starts from the beginning of 2005 and terminates at the end of 2016.

3.2. The empirical strategy

We are interested in when surprises happened in the Japanese bond futures market during the period of 2005 through 2016 and how much. The key to applying our model to the actual data is to find the series of the fair price, p_τ. Based on it, we identify the upper bound of ask prices, $\overline{p}_{a\tau}$, and the lower bound of bid prices, $\underline{p}_{b\tau}$. Based on them, we can quantify surprises finally. Below, we explain our non-parametric empirical methodology step by step (see Figure 4).

The fair price, p_τ, is estimated as follows. The fair price is updated when new public information arrives, but untouched until then. A question is how to identify the timing that market participants receive the public information. To do so, we exploit the following simple facts. First, ask prices are always above bid prices. Bid prices are never above ask prices. Second, the fair price is always in between ask prices and bid prices. Hence, we can say that traders have already received new public information, when we observe (ii) a bid price which is above the fair price or (ii) an ask price which is below the fair price. In this paper, the fair price is updated to this bid or ask price.

The upper bound of ask prices, $\overline{p}_{a\tau}$, is estimated as follows. Ask prices, $p_{a\tau}$'s ,

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[12] Trading hours have been changed several times during our data period. The day session consists of the morning session and the afternoon session. Currently, the morning session is open from 8:45 to 11:02, whereas the afternoon session is open from 12:30 to 15:02. Prior to November 21, 2011, the corresponding hours were from 9:00 to 11:00 and from 12:30 to 15:00, respectively. While the night session starts from 15:30, its closing time has been gradually extended. It was 18:00 prior to November 21, 2011, 23:30 prior to March 24, 2014, 3:00 prior to July 19, 2016, and is currently 5:30.

fluctuate around an old fair price, $p_{\tau-1}$, until a new fair price, p_τ, arrives. As shown in the previous section's simulation analysis, the distribution of asset prices has fat tails when the market is driven by participants' herding behavior. Therefore, with $\lambda_a = 1$, asset prices are likely to reach, or at least very close to, the upper bound frequently. Thus, $\overline{p}_{a\tau}$ can be approximated by the maximum value of $p_{a\tau}$'s. Similarly, assuming $\lambda_b = 1$, the lower bound of bid prices, $\underline{p}_{b\tau}$, is approximated by the minimum value of $p_{b\tau}$'s.

A few caveats are in order here. First, to deal with the noise in data, we make some allowance for the detection of the arrival of public information. To be precise, we say that traders have received new public information, either if a bid price rises three basis points above the fair price or if an ask price falls three basis points below the fair price. The size of the allowance can be chosen arbitrarily. Note however that if the allowance were set too big, important public information could be discarded unintentionally together with noises. Thus, the size of the allowance should be chosen carefully.

Second, some conditions should be satisfied to justify the approximation of $\overline{p}_{a\tau}$ by the maximum price observed in between the release of $p_{\tau-1}$ and of p_τ. Recall the simulation analysis in the previous section. With $\theta_{\tau-1}$, $q_{a\tau}$, and $q_{b\tau}$ given, the distribution of asset prices is more fat-tailed, as $\mu_H - \mu_L$ is larger and/or as σ is smaller. Therefore, the approximation is good, if traders receive private information sufficiently valuable to infer the marginal value of future public information. Otherwise, we underestimate traders' expected marginal value of future public information.

3.3. *A bird's-eye view of fair prices and surprises*

Figure 5 presents the estimated series of the fair price. As shown in the figure, p_τ follows an upward trend, and θ_τ a downward trend. Interestingly, the estimate of θ_τ began falling well before the financial crisis hit the global economy. From the business cycle point of view, this implies that the Japanese economy began to slow down and got into a recession phase before the crisis started.

Figure 6 shows the estimated series of marginal value of public information, realized and expected. The realized marginal value of public information, η_τ, is calculated from the estimate of θ_τ and $\theta_{\tau-1}$.[13] As shown in Figure 6(a), it fluctuates wildly when the Lehman Brothers bankrupted in September 2008. In the same figure, we see that the range of fluctuation expanded two more times thereafter, i.e., around the East Japan Great Earthquake and the BOJ's introduction of quantitative and qualitative monetary easing. Looking at the series closely, we also find relatively large fluctuations around the launching of the negative interest rate policy and the yield curve control policy.

Figure 6(b) provides the estimates of $\eta_{a\tau}$ and $\eta_{b\tau}$, which are obtained from $\overline{p}_{a\tau}$ and $\underline{p}_{b\tau}$ through equations (14) and (15). It appears that the range defined by $[\eta_{a\tau}, \eta_{b\tau}]$ widened together with the enlargement of the fluctuation of η_τ. Recall that $\eta_{a\tau}$ and $\eta_{b\tau}$ indicate traders' expected marginal value of public information based on their private information. The simultaneity among their fluctuations implies that traders' expectations are not far from reality.

Figure 7 shows how many times surprises happened in the Japanese bond futures market and how much. As easily expected, spikes are observed around the Lehman Brothers bankruptcy, the East Japan Great Earthquake, BOJ's introduction of quantitative and qualitative monetary easing. Table 1 is the list of the twenty largest surprises, on long and short sides, that have happened since 2005. The biggest surprises that led to higher interest rates happened on April 5, 2013, i.e., the next day of the Bank's introduction of quantitative and qualitative monetary easing. The biggest surprises that led to lower interest rates happened a week later, when the Bank had a meeting with market participants to exchange their views on the current and future market.

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[13] To calculate $\eta_{a\tau}$ and $\eta_{b\tau}$, we set p_H=1.1×the highest sample ask price and p_L= 0.9×the lowest sample bid price. In this paper, p_H and p_L are assumed constant. The assumption, however, is unrealistic from a long-run perspective. It is natural to think that these parameters will change if the potential rate of growth or mid- to long-term inflation rates change over time. Thus, when taking the current empirical strategy, we should be careful that the sample period is not too long.

Interestingly, if some extreme cases are excluded, the frequency of surprises appears to have increased, while the amount of surprises seems to have decreased recently. This implies that traders have experienced small surprises many times. This situation is likely to continue, since traders have only a small incentive to incur costs to improve their prediction further, when prediction errors are small. We will be back to this issue later when analyzing the sensitivity of traders to various economic indicators.

3.4. Market reactions to the four selected policy announcements

In this paper, we are interested in how monetary policy announcements changes, or do not change, the behavior of market participants. Here we focus on the four policy announcements made recently by the BOJ: the introduction of quantitative and qualitative monetary easing (QQE I) on April 4, 2013; the enlargement of quantitative and qualitative monetary easing (QQE II) on October 31, 2014; the introduction of negative interest rate policy (NIR) on January 29, 2016; the launching of yield curve control (YCC) on September 21, 2016. The analysis below indicates the following fact: Having experienced the BOJ governor Kuroda's bazooka shot of QQE I, traders has become rather quick to learn BOJ's intention embedded in its policy announcements.

Figure 8 shows the intra-day behavior of the fair price, p_τ, on the selected days. The dots indicate the timing of fair price updates. The fair price began to swing up and down in a large scale immediately after the BOJ's announcement of QQE I. The large swing continued for a long time into the next day.[14] In contrast, after the announcements of NIR and YCC, the adjustment of the fair price was completed fairly quickly and concentrated around the announcement time.

The figure highlights difficulty of central bank communication at the time of a policy shift. When QQE I was announced on April 4, 2013, traders received it as the BOJ's signal of lowering interest rates further (Figure 8(a)). On the next day, however,

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[14] It is also notable that the fair price was updated many times in the morning session on the day of QQE I.

the traders reinterpreted the Bank's policy intention wrongly as indicating that it would allow interest rates to rise. The confusion had continued for a long time in the market until the Bank had a meeting with main traders a week later. This meeting caused large market surprises in the direction the Bank intended.

Figure 9 shows the marginal value of public information which appeared during every five minutes and its decomposition into expected and unexpected components. Following the announcement of QQE I, public information appeared dispersedly over 380 minutes. In contrast, the appearance of public information was concentrated around the time of policy announcement in the case of NIR and YCC. Similarly, surprises are observed dispersedly over six hours, following the announcement of QQE I. In contrast, the happening of surprises was concentrated during the two hours after the policy announcement in the case of NIR and YCC.[15]

Figure 10 shows the market responses over longer horizons. Figure 10(a) indicates how much the fair price was updated on the day of policy announcement and over the next five days. In the case of QQE I, the fair price was updated mostly after the announcement day. In contrast, more than half of the update was completed on the day of policy announcement in the case of NIR and YCC. A similar result is obtained for surprises. As shown in Figures 10(b) and (c), the surprises happened mostly after the announcement day in the case of QQE; in contrast, they were observed on the very day of policy announcements in the case of NIR and YCC.

3.5. Market behavior immediately before the four selected policy announcements

Here we examine the market behavior immediately before the announcement of the four selected policy changes. First, we show that traders reinforced herding behavior

[15] Note the big surprise recorded just before the BOJ announced the NIR policy on January 29, 2016. This was due to the report by the Nikkei wired news "the BOJ has discussed setting a negative interest rate", which broadcast its monetary policy outlook before the BOJ's announcement. Interestingly, no surprises happened in the case of QQE II. This is because a lot of uncertainty had been already prevailed in the market due to the announcement by GPIF before the BOJ's policy announcement and due to the delay of the policy announcement, as discussed later.

after they experienced QQE I. This guarantees that the underestimation of traders' expected marginal value of public information is avoided at least in the after-QQE I sample. In Figure 11, the inversed cumulative distribution of returns in the morning session on the announcement day is compared with the corresponding distribution observed four business days before the announcement (i.e., on the previous day of the "blackout" before the monetary policy meeting). As in Figure 11(a), the two distributions coincide mostly with each other in the case of QQE I. As for QQE II, NIR, and YCC, however, it is indicated in Figures 11(b) to (d) that the distribution on the announcement day diverts upward from the corresponding distribution observed four business days before the announcement.

In Figure 12, the bars indicate the sum of $\eta_{a\tau}$ and $\eta_{b\tau}$. The size of $\eta_{a\tau}$ and $\eta_{b\tau}$ shows how large profit opportunities traders expect. We see that traders' expectations were larger on the announcement days of QQE II and YCC than on those of QQE I and NIR. This reflects partly a lot of uncertainty that prevailed on the day due to the policy announcements by the GPIF in the case of QQE II and prior notice of publishing comprehensive assessment by the BOJ in the case of YCC. There was, however, another source of uncertainty on these days. In the same figure, we show the time gap between the opening of the afternoon session and the release of the policy announcement. Clearly, traders' expectations are correlated with the time gap positively.

As shown in Figure 13(a), positive correlation has been observed between the expectations of traders and the delay of policy announcement since Governor Kuroda took the current position. As the announcement delays, market participants expect a substantial policy change to be made. This increases traders' expected marginal value of public information. In contrast, as shown in Figure 13(b) and (c), no correlation had been observed in the Shirakawa and Fukui regimes. It is also noteworthy that as shown in Figure 14(a), no (or even negative) correlation is observed on the short side. This means that traders' expectations are biased towards monetary easing rather than tightening.

As a related issue, it is interesting to see the effects of live broadcasting of press conference after policy announcements on market surprises. On April 8 of 2014, the BOJ began to broadcast the Governor's press conference after the monetary policy meeting on spot usually from 15:30 through 16:30. As shown in Figure 15, on average, surprises has halved on the long side and has mostly extinguished on the short side. Quick and direct communication saves market participants from misunderstanding the Bank's policy announcement.

3.6. Market reactions to the release of economic indicators

Not only the central bank policy announcement but economic indicators are also important public information available in financial markets. Here we examine how market participants' reaction to economic indicators has changed or not recently. In particular, we focus on traders' response to the release of the Indices of Industrial Production (IIP), the Consumer Price Index (CPI), and the Economy Watcher Survey (EWS).

Figure 16 shows the size of fair price updates in reaction to the release of the three economic indicators. Clearly, since QQE I, the size of reactions to the release of IIP has shrunk by half on average. The size of reactions to the release of CPI is more than halved. Interestingly, the size of reactions to the release of EWS has been reduced only on the long side, meaning that market participants take the Survey as a useful source to look out the downturn of the asset price or on the upturn of the interest rate. On the other hand, as shown in Figure 17, traders' expectations about the marginal value of private information have not reduced so much as the realized marginal value of public information. As a result, market surprises have recently become smaller, as shown in Figure 18.

Several explanations are possible for a downsizing of fair price updates. First, it may be that the interest rate has only a small room to move near the zero lower bound. If this is the case, the fair price updates become asymmetric. However, the fair price does not move downward as well as upward. In addition, the fair price is more responsive both downward and upward to the announcement after the BOJ's monetary policy meeting, as shown in Figure 19. Thus, this explanation is not plausible. Second, it may be that the movements of the economic indicators have been reduced. This explanation is also implausible, when we look at the time series of these indicators, as shown in Figure 20.

The third and the most plausible explanation is that the tendency has recently been strengthened that market participants learn the meaning of each indicator not from their experiences but from the interpretation by the BOJ. We support this explanation not by the amount of fair price updates but by the time to fair price updates. Figures 21(a) and (b) indicate how long it takes for the fair price to make the first reaction to the release of economic indicators as well as to the announcement of central bank policies. The speed at which traders react to economic indicators, such as the IIP and the CPI, has become slower since 2011.

In contrast, the speed at which traders respond to the BOJ's announcements is very quick. Figures 21(c) and (d) show how many minutes it takes for the fair price to react to the release of the statements by the BOJ. After the QQE I was introduced, market participant became less sensitive to the Bank's release of the result of monetary policy meeting temporarily. But their sensitivity has strengthened again since the QQE II. A similar tendency is observed for the reaction to the release of the asset purchase schedule by the Bank. After QQE II, market participants became less sensitive to the BOJ's announcement of a monthly schedule of government bonds purchases. But the sensitivity has returned to its normal level since the NIR policy.

In this context, it is interesting to see the effects of reducing monetary policy meetings on market behavior. Since the year of 2016, the annual frequency of BOJ's monetary policy meetings has been reduced from fourteen to eight times a year. Instead, the issuance of the Outlook for Economic Activity and Prices, the BOJ's economic outlook, has been increased from twice to four times a year. However, the Outlook has richer information than the Monthly Reports released after the monetary policy meeting.[16] A question is whether the BOJ's information transmission has weakened or not.

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[16] The Monthly Report of Recent Economic and Financial Developments has been integrated into the Outlook since the year of 2016.

Figure 22 shows the reaction of the fair price after the release of reports. The reaction to the Outlook is greater than that to the Reports on average. Interestingly, the total reaction to the two Outlooks and the twelve Reports issued in 2015 is almost the same as that to the four Outlooks issued in 2016. The new publication scheme allows the BOJ to send the same amount of information value to the market. It is also shown that the expected value of the four Outlooks is the same as the expected value of the two Outlooks and the twelve Reports. The amount of public information generated by the BOJ has not been reduced by the reduction of the number of monetary policy meetings.

4. CONCLUSION

In this paper, we extend Nirei, et al. (2013) and Kamada and Miura (2014) to present the theoretical model to explain how traders incorporate public and private information into asset prices. We also propose the empirical framework that enables us to fit the model to tick-by-tick data and to identify surprises in financial markets, particularly those in the Japanese bond futures market.

Many shocking events happened and caused large surprises in the Japanese bond futures market during the period of 2005 through 2016. The first surprising shocks came with the Lehman Brothers bankruptcy in 2008; the second with the Great East Japan Earthquake in 2011; the third with the BOJ's introduction of quantitative and qualitative monetary easing in 2013. The tapering speech by then Federal Reserve Chairman Ben S. Bernanke in 2013 was also received by financial traders with large surprises.

The empirical analysis also shows that drastic changes occurred in the sensitivity of bond futures prices to BOJ's monetary policy announcements. We closely examined the intra-day developments of market participants' beliefs. We see that their reactions to the introduction of negative interest rate policy on January 29, 2016 and yield curve control on September 21, 2016 were much quicker than those to the introduction of quantitative and qualitative monetary easing on April 4, 2013 and its enlargement on October 31, 2014.

Market participants are now so sensitive to the BOJ's policy actions that the delay of statement release after monetary policy has a substantial impact on the price formation in bond futures markets. In this context, the live press conference broadcast after monetary policy meetings, which was introduced on April 8, 2014, was effective to reduce surprises in bond futures markets. Furthermore, the early announcement of operation scheduled dates, which was introduced in 2017, would be useful to minimize market surprises.

In contrast, traders' sensitivity to other economic indicators has weakened. The impact of the Indices of Industrial Production, the Consumer Price Index, and the Economy Watcher Survey on bond futures prices is smaller than it was before the introduction of quantitative and qualitative monetary easing. Interestingly, the information value of the BOJ's economic analysis has not decreased, even though the Bank has reduced the frequency of monetary policy meetings from fourteen to eight times a year and that of economic reports from monthly to quarterly.

APPENDIX. PROOF OF THE EXISTENCE OF MARKET EQUILIBRIUM

Lemma 1. $\bar{x}_\tau(k)$ is monotonically decreasing in k when n_a is sufficiently large. $\underline{x}_\tau(h)$ is monotonically increasing in h when n_b is sufficiently large.

Transforming equation (11) yields

$$V_{a\tau}(k) = A\big(\bar{x}_\tau(k)\big)^{n_a-k} B\big(\bar{x}_\tau(k)\big)^{k-1} \delta(\bar{x}_\tau(k)) \tag{A1}$$

where

$$V_{a\tau}(k) \equiv \frac{(1-q_{a\tau}) - q_{a\tau}\dfrac{1}{\theta_{\tau-1}}\dfrac{p_H - p_{a\tau}(k)}{p_{a\tau}(k) - p_L}}{(1-q_{a\tau})\dfrac{1}{\theta_{\tau-1}}\dfrac{p_H - p_{a\tau}(k)}{p_{a\tau}(k) - p_L} - q_{a\tau}}. \tag{A2}$$

Taking the log of both sides of equation (A1) yields

$$ln\frac{A(\bar{x}_\tau(k))}{B(\bar{x}_\tau(k))} + ln\frac{V_{a\tau}(k+1)}{V_{a\tau}(k)}$$

$$= (n_a - k - 1)ln\frac{A(\bar{x}_\tau(k+1))}{A(\bar{x}_\tau(k))} + kln\frac{B(\bar{x}_\tau(k+1))}{B(\bar{x}_\tau(k))} + ln\frac{\delta(\bar{x}_\tau(k+1))}{\delta(\bar{x}_\tau(k))}. \quad \text{(A3)}$$

The first term on the left-hand side is positive since $A(x) > B(x)$. It is clear from equation (16) that as n_a increases, the difference between $(k+1)/n_a$ and k/n_a converges to zero, and so does the difference between $p_{a\tau}(k+1)$ and $p_{a\tau}(k)$. Thus, the difference between $V_{a\tau}(k+1)$ and $V_{a\tau}(k)$ converges to zero, and so does the second term on the left-hand side. This implies that the left-hand side of equation (A3) is positive when n_a is sufficiently large. Since $A(x)$, $B(x)$, and $\delta(x)$ are all decreasing in x, the right-hand side is positive only if $\bar{x}_\tau(k) > \bar{x}_\tau(k+1)$. This shows that $\bar{x}_\tau(k)$ is decreasing in k. Similarly, we can show that $\underline{x}_\tau(h)$ is increasing in h when n_b is sufficiently large.

Proposition 1. There exists a k^* that satisfies $\Gamma_{a\tau}(k^*) = k^*$ when n_a is sufficiently large. Moreover, there exists an h^* that satisfies $\Gamma_{b\tau}(h^*) = h^*$ when n_b is sufficiently large.

We know from Lemma 1 that $\bar{x}_\tau(k)$ is monotonically decreasing in k. Thus, $\Gamma_{a\tau}$ is a monotonic mapping. Therefore, following Nirei et al. (2013), we can show the existence of equilibrium k^* using Tarski's fixed point theorem for a discrete monotonic mapping. The existence of equilibrium h^* can be proved in a similar manner.

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Table 1. The 20 Largest Surprises

(a)Low interest rates surprises

Ranking	Date	Event	Surprise
1	2013/4/11	The BOJ had a meeting with market participants to exchange their views on the current and future market (4/11)	0.01326
2	2008/9/16	Bankruptcy of Lehman Brothers (9/15)	0.01310
3	2013/4/5	Introduction of QQE by the BOJ (4/4)	0.01073
4	2008/9/10	Fannie Mae and Freddie Mac went under Federal control (9/7)	0.00945
5	2013/5/23	Tapering speech by Federal Reserve Chairman Bernanke (5/22)	0.00781
6	2008/10/29	Mounting expectation of interast rate cuts at the forthcoming BOJ policy meeting (10/29)	0.00778
7	2013/4/12	Governer Kuroda made a speech in Tokyo for the first time after the introduction of QQE (4/12)	0.00639
8	2007/11/2	Governer Fukui was summoned to the House of Representatives, Financial Monetary Committee (11/2)	0.00567
9	2013/5/15	The BOJ offered 2.8 trillion yen under the funds-supplying operation (5/15, afternoon)	0.00543
10	2007/12/12	The FOMC announced interest rate cut by 25bps (12/11)	0.00543
11	2007/11/27	Decline in U.S. interest rates due mainly to the subprime mortgage problem (11/26)	0.00453
12	2011/3/14	The Great East Japan Earthquake (3/11)	0.00394
13	2013/6/25	Strong demand for JGBs in the auction for enhanced-liquidity. The bid-to-cover ratio was 5.95 (6/25)	0.00394
14	2006/9/22	——	0.00394
15	2013/6/13	Member of the BOJ Policy Board Shirai made a speech in Asahikawa (6/13)	0.00379
16	2013/5/22	The BOJ maintained the current policy (5/22)	0.00374
17	2007/8/29	——	0.00369
18	2008/5/16	——	0.00363
19	2013/5/17	The BOJ offered outright purchase of 1.3 trillion yen JGBs (5/17)	0.00358
20	2009/3/19	The FOMC announced the starting of Treasury purchases (3/18)	0.00352

c.f.

60	2016/1/29	Introduction of NIR by the BOJ (1/29)	0.00200
71	2016/9/21	Introduction of YCC by the BOJ (9/21)	0.00178

Note. After surprises are quantified as $\left(\log \overline{p}_{a\tau} - \log p_{\tau}\right)^{+}$, each day is ranked by aggregate surprises within the day.

(b) High interest rates surprises

Ranking	Date	Event	Surprise
1	2013/4/5	Introduction of QQE by the BOJ（4/4）	-0.01537
2	2006/6/9	Calendar rollover（6/9）	-0.01203
3	2013/5/15	It was reported that the Cabinet Ministers implied that a rise in interest rates was not an issue （5/14）	-0.01178
4	2013/5/23	Tapering speech by Federal Reserve Chairman Bernanke（5/22）	-0.00989
5	2010/12/9	Calendar rollover（12/9）	-0.00874
6	2006/3/9	Termination of QE by the BOJ（3/9）	-0.00862
7	2007/3/9	Calendar rollover（3/9）	-0.00779
8	2008/6/11	Calendar rollover（6/11）	-0.00771
9	2008/5/23	——	-0.00764
10	2013/4/8	A circuit breaker was triggered in the JGB futures market（4/8）	-0.00739
11	2008/10/9	The BOJ did not coordinate with accomodative interest rate cuts by six central banks in the U.S. and Europe（10/8）	-0.00562
12	2005/3/10	Calendar rollover（3/10）	-0.00544
13	2013/5/24	Tapering speech by Federal Reserve Chairman Bernanke（5/22）	-0.00513
14	2013/4/12	Governer Kuroda made a speech in Tokyo for the first time after the introduction of QQE（4/12）	-0.00500
15	2013/4/11	The BOJ had a meeting with market participants to exchange their views on the current and future market（4/11）	-0.00492
16	2008/6/13	The BOJ's monetary policy meeting（6/13）	-0.00475
17	2013/12/11	Calendar rollover（12/11）	-0.00443
18	2008/11/14	The Ministry of Finance held a meeting of JGB Market Special Participants（11/14）	-0.00384
19	2010/12/15	The BOJ released the results of December 2010 Tankan survey （12/15）	-0.00367
20	2007/6/13	——	-0.00366

Note. After surprises are quantified as $\left(\log p_{\underline{b}\tau} - \log p_\tau\right)^-$, each day is ranked by aggregate surprises within the day.

Figure 1. Demand Function of Long-Side Informed Traders

(a) Investment Decision-making based on private information

(b) Shape of the demand function

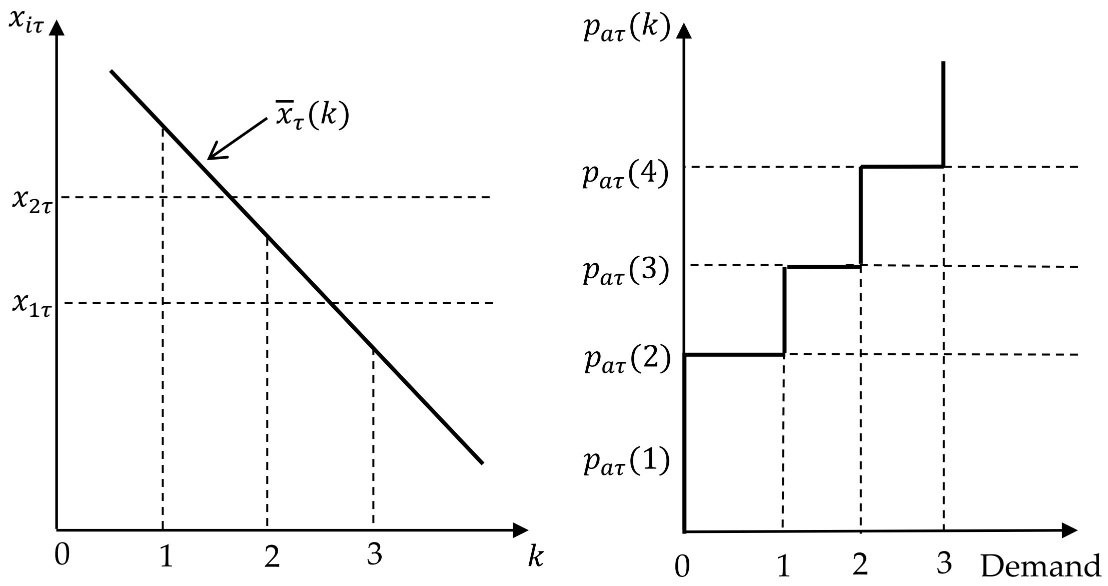
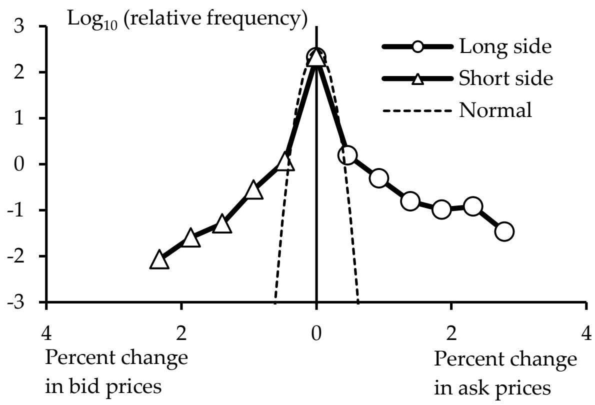


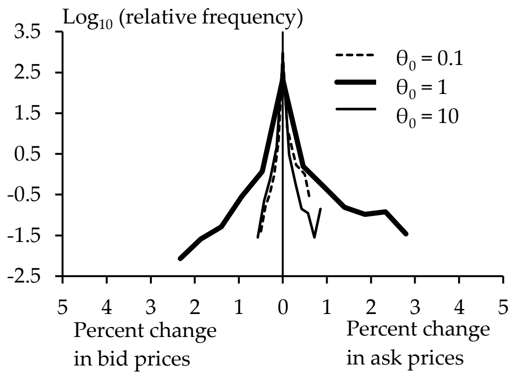
Figure 2. Fat-Tail Distribution of Asset Prices



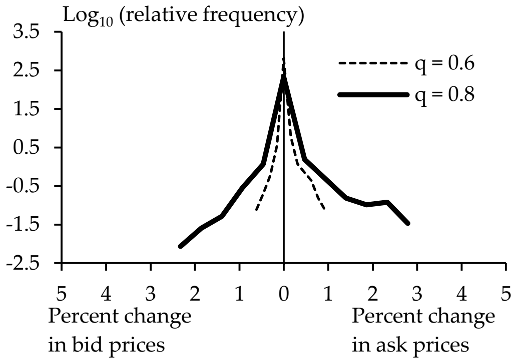
Note. Private information is generated from F_H. The simulation is iterated 25,000 times each for long and short side.

Figure 3. Comparative Statics of the Asset Price Distribution

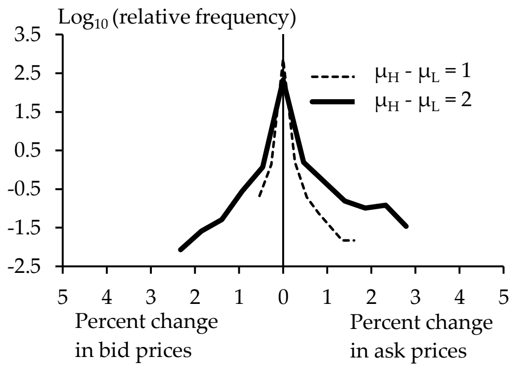
(a) Effects of likelihood ratios



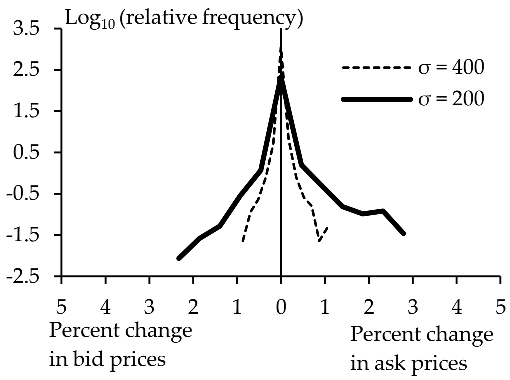
(b) Effects of traders' expected marginal value of public information



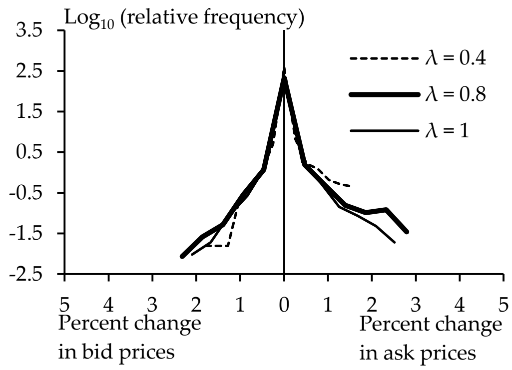
(c) Effects of accuracy of private information (mean difference)



(d) Effects of accuracy of private information (standard deviation)



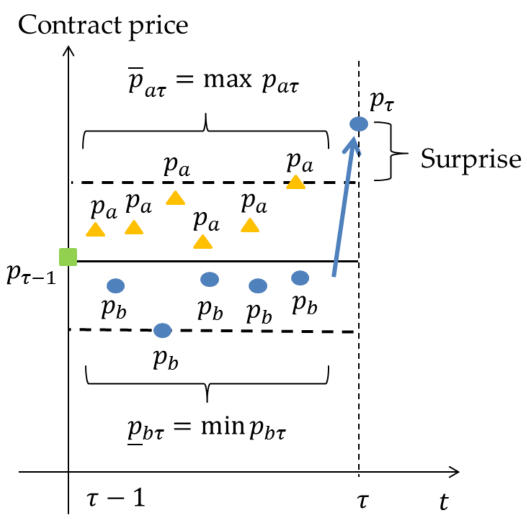
(e) Effects of market liquidity



Note. Private information is generated from F_H. The simulation is iterated 25,000 times each for long and short side.

Figure 4. Fitting the Model to Tick-by-Tick Data

(a) Surprises identified



(b) No surprises identified

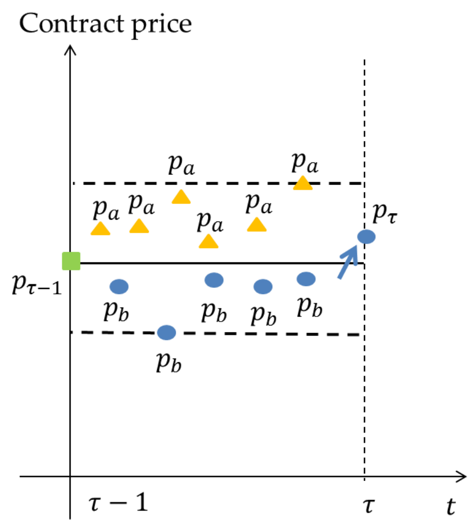
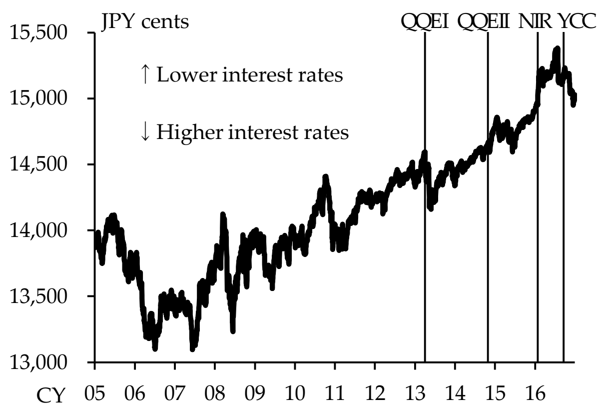
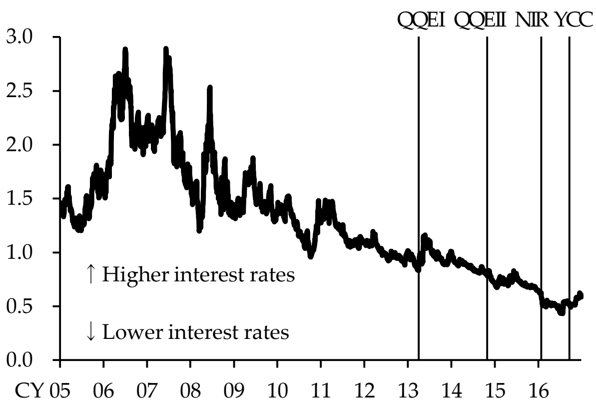


Figure 5. Fair Prices and Traders' Beliefs

(a) Estimated fair prices



(b) Traders' beliefs on financial states

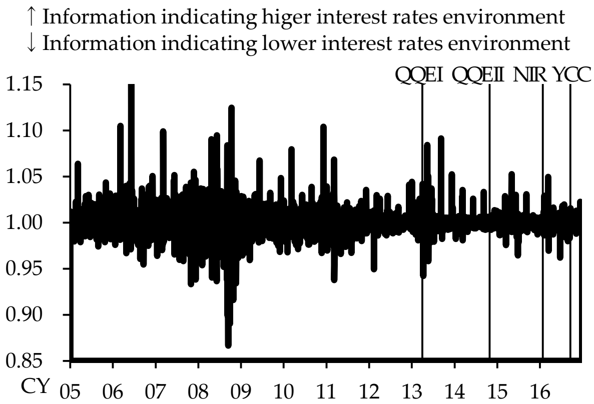


Notes 1. Four vertical lines in each chart correspond to QQE I on April 4, 2013, QQE II on October 31, 2014, NIR on January 29, 2016, and YCC on September 21, 2016, respectively. This applies to the following figures.

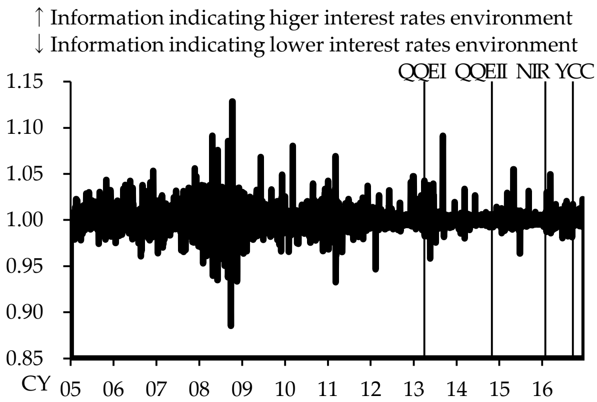
2. Figures are averaged on each day.

Figure 6. Expected and Realized Marginal Value of Public Information

(a) Realized marginal value of public information



(b) Expected marginal value of public information



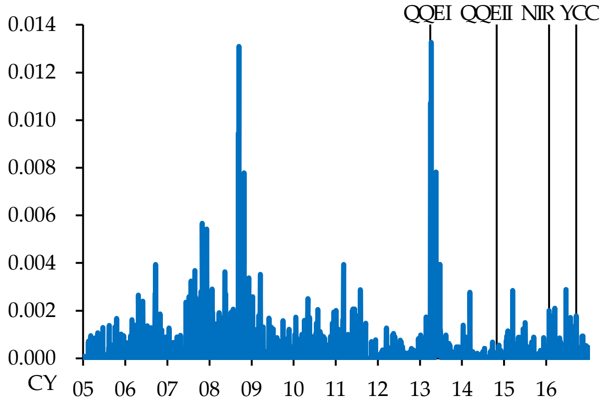
Notes 1. The realized marginal value of public information is depicted as the range between the maximum and the minimum value of η_τ within each day.

2. The expected marginal value of public information is depicted as the range between the maximum value of $\eta_{b\tau}$ and the minimum value of $\eta_{a\tau}$ within each day.

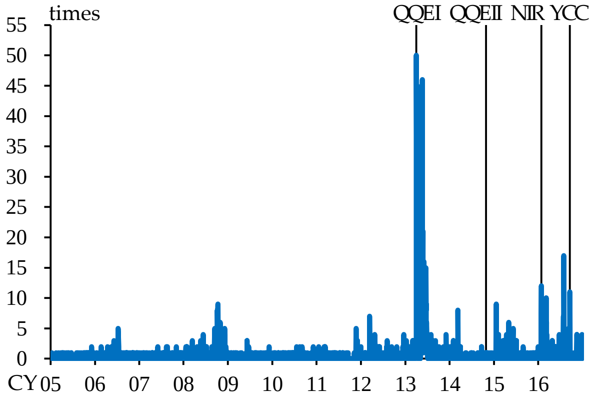
Figure 7. Surprises

(a) Low interest rates surprises

(a-1) Amount of surprises

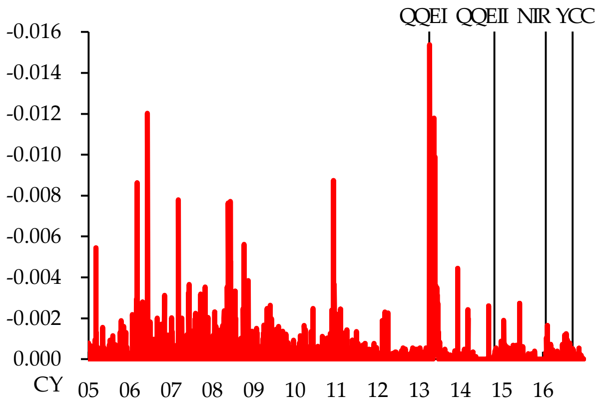


(a-2) Frequency of surprises

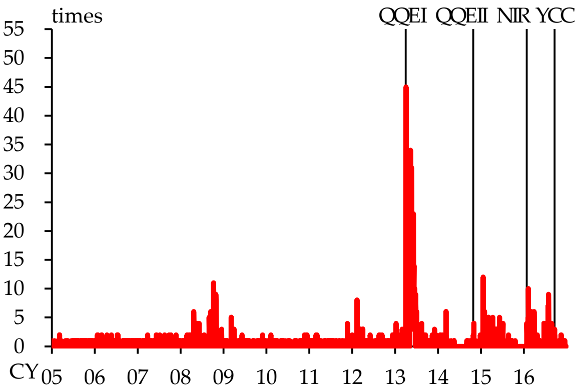


(b) High interest rates surprises

(b-1) Amount of surprises



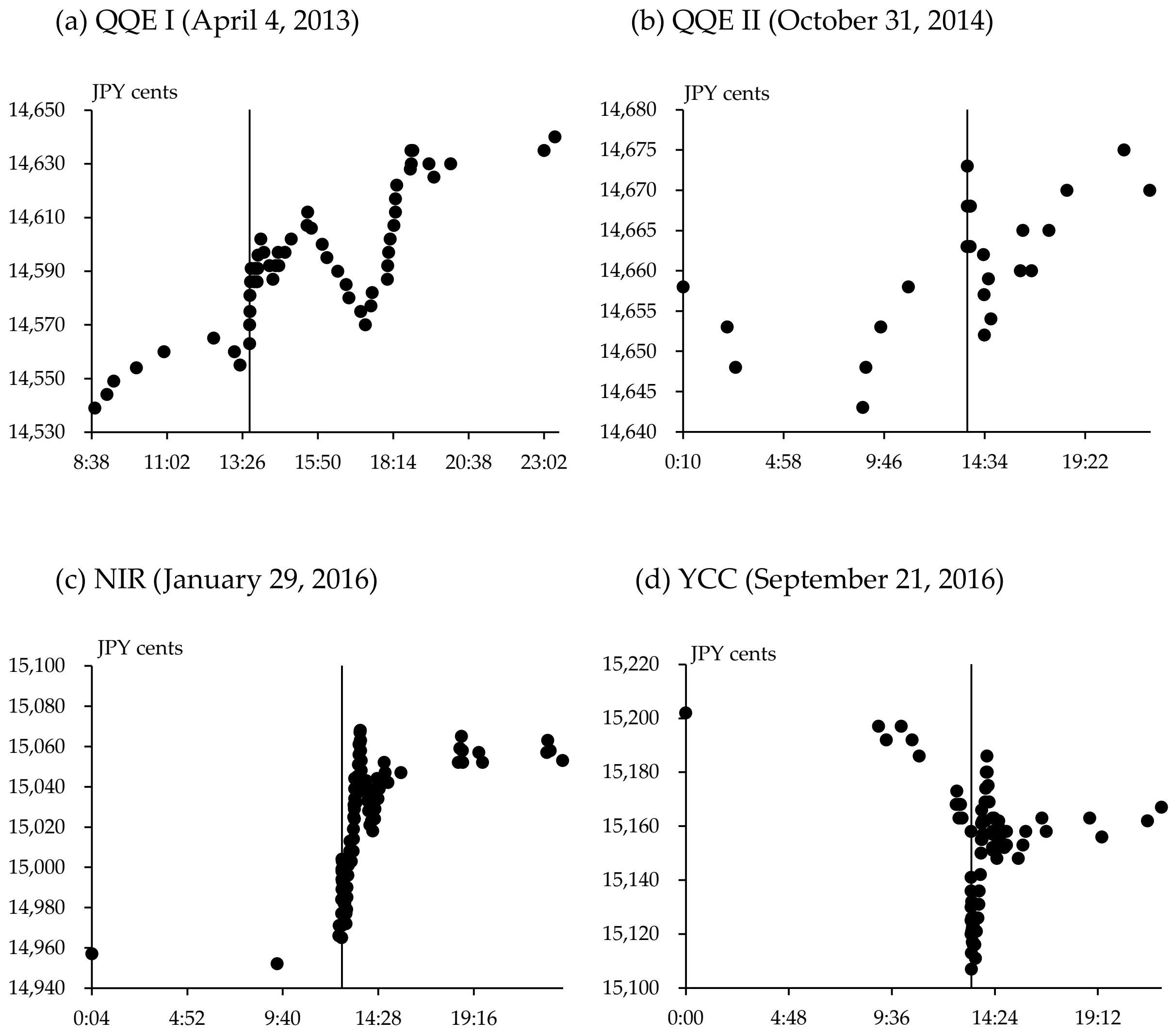
(b-2) Frequency of surprises



Notes 1. Low and high interest rates surprises are quantified as $\left(\log \overline{p}_{a\tau} - \log p_\tau\right)^+$ and $\left(\log \underline{p}_{b\tau} - \log p_\tau\right)^-$, respectively.

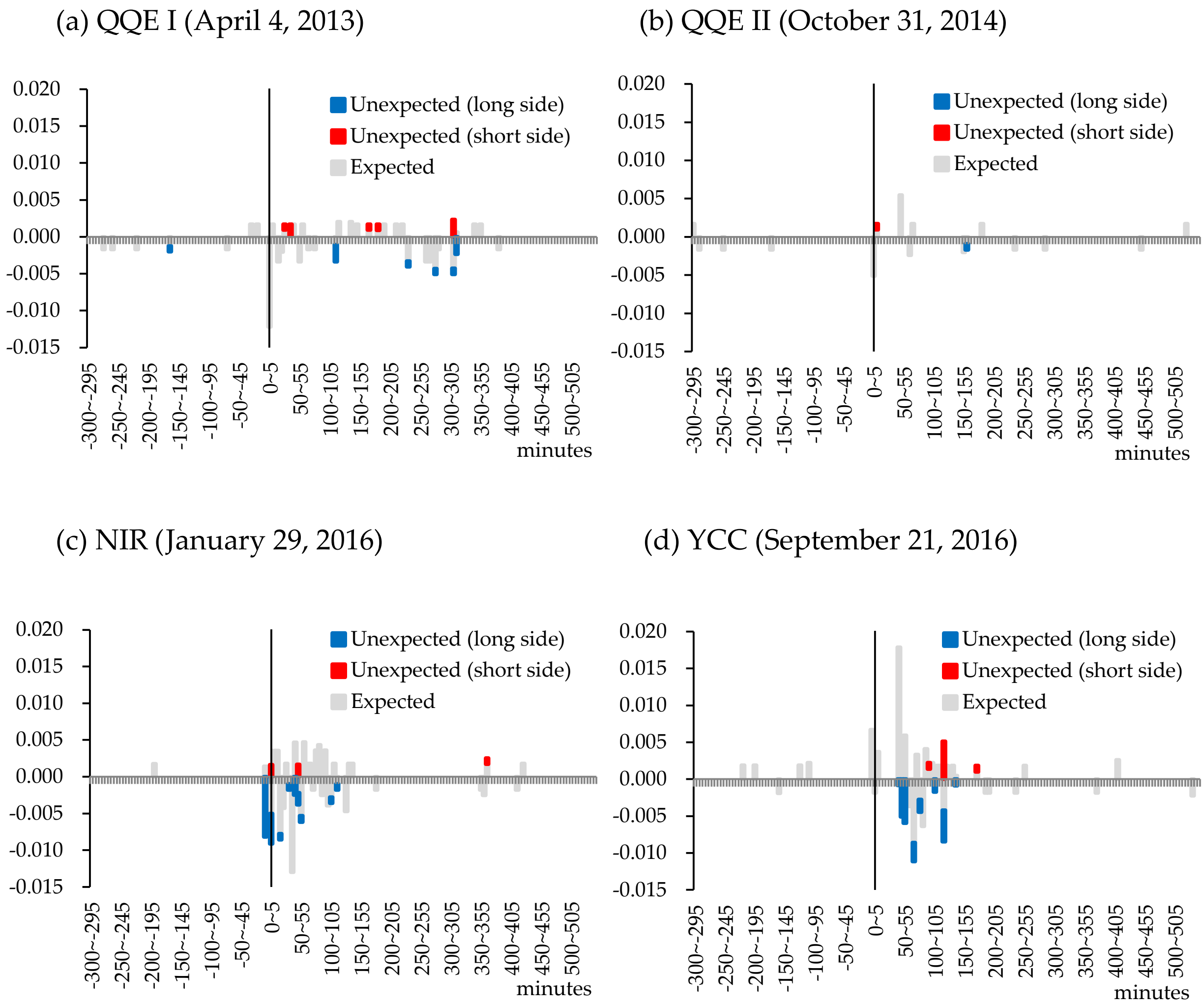
2. Figures are aggregate on each day.

Figure 8. Intra-Day Developments of Fair Prices



Note. Vertical lines correspond to announcement time.

Figure 9. Expected and Unexpected Marginal Value of Public Information

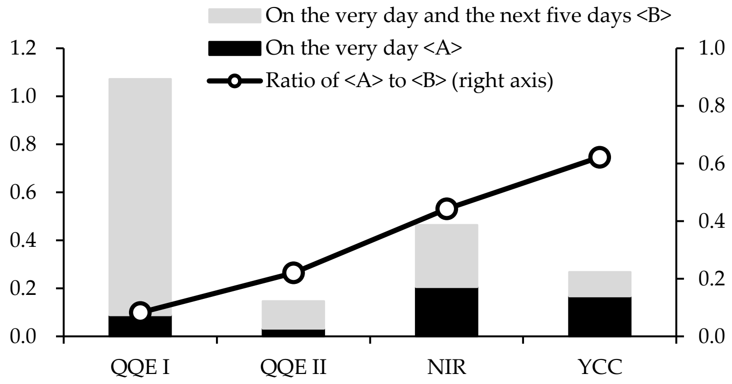


Notes 1. Unexpected components are surprises quantified as $(\log \eta_{a\tau} - \log \eta_\tau)^-$ or $(\log \eta_{b\tau} - \log \eta_\tau)^+$. Expected components are derived by subtracting unexpected components from log marginal value of public information, $\log \eta_\tau$.

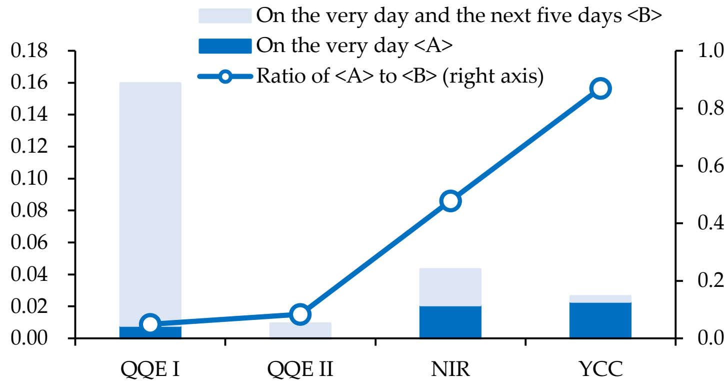
2. Vertical lines correspond to announcement time adjusted to zero. Figures are summed up at the timing of fair price updates at intervals of five minutes.

Figure 10. Market Responses Observed over Longer Horizon

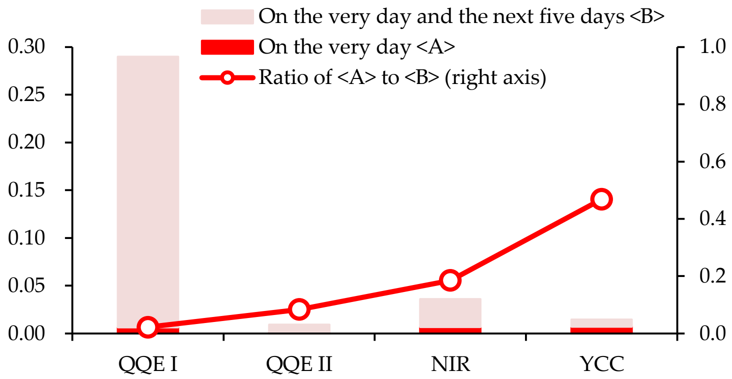
(a) Frequency of fair price updates



(b) Low interest rates surprises



(c) High interest rates surprises

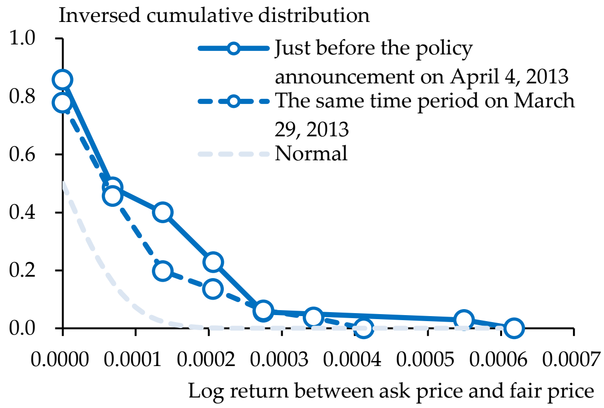


Notes 1. The frequency of fair price updates is weighted by the absolute information value, $|\log \eta_\tau|$. Low and high interest rates surprises are quantified as $(\log \eta_{a\tau} - \log \eta_\tau)^-$ and $(\log \eta_{b\tau} - \log \eta_\tau)^+$, respectively.

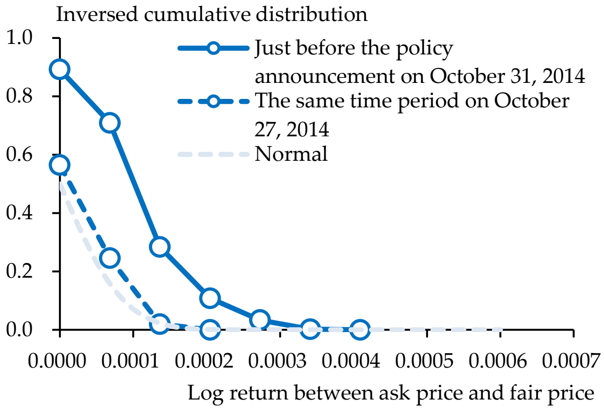
2. Figures on the very day are summed up at intervals between the policy announcement and the closing of the subsequent night session.

Figure 11. Herding Behavior Reinforced before Policy Announcements

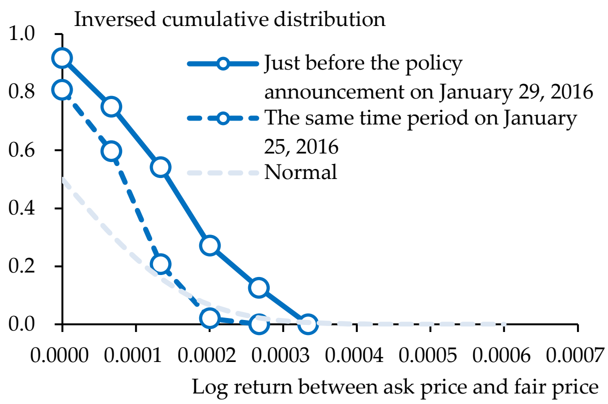
(a) QQE I (April 4, 2013)



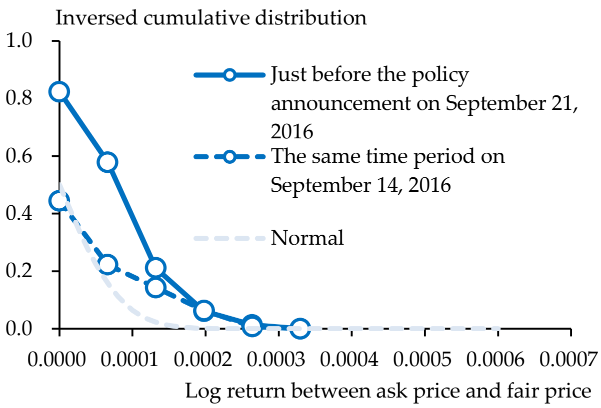
(b) QQE II (October 31, 2014)



(c) NIR (January 29, 2016)

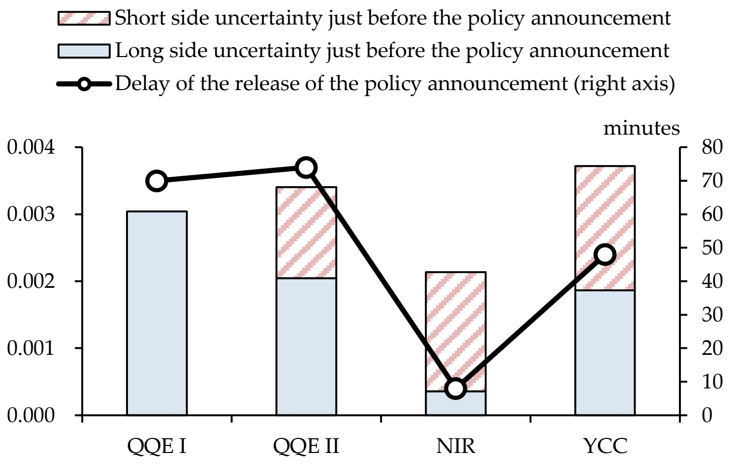


(d) YCC (September 21, 2016)



Note. Normal distributions are depicted as a reference, where mean is zero and standard deviation is equal to median of the distribution observed four business days ahead of policy announcements.

Figure 12. Uncertainty Enlarged by Policy Announcement Delays

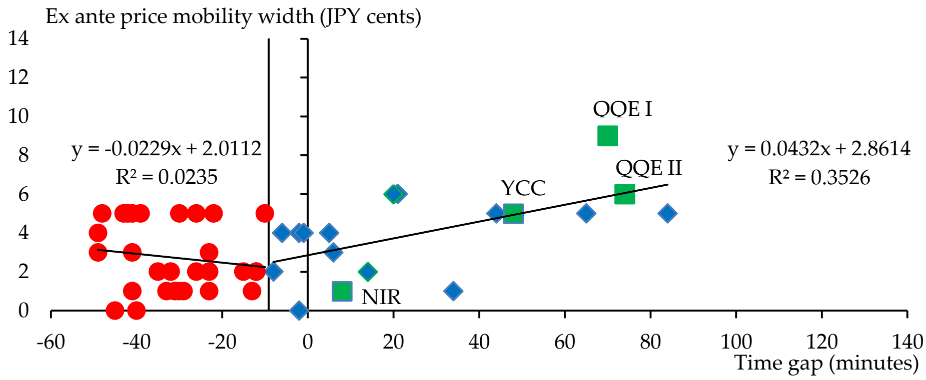


Notes 1. Long and short side uncertainty is given by $|\log \eta_{a\tau}|$ and $|\log \eta_{b\tau}|$, respectively.

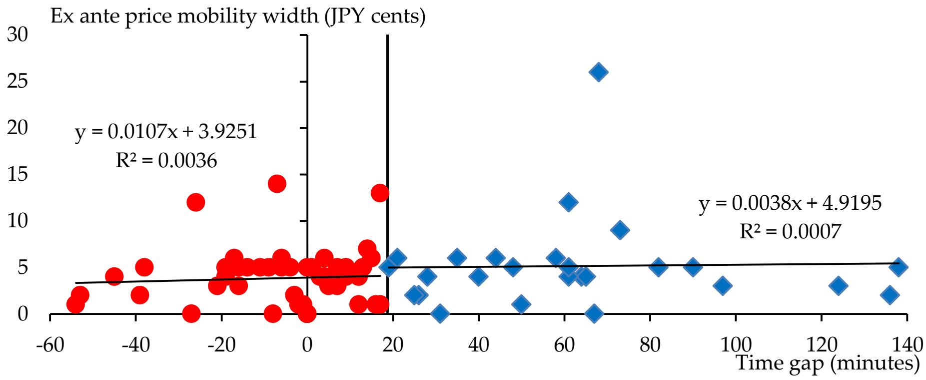
2. Delay of the release of the policy announcement is given by the time gap between the opening of the afternoon session (i.e., 12:30) and the release of the policy announcement.

Figure 13. Market Reaction to Policy Announcement Delays on the Long Side

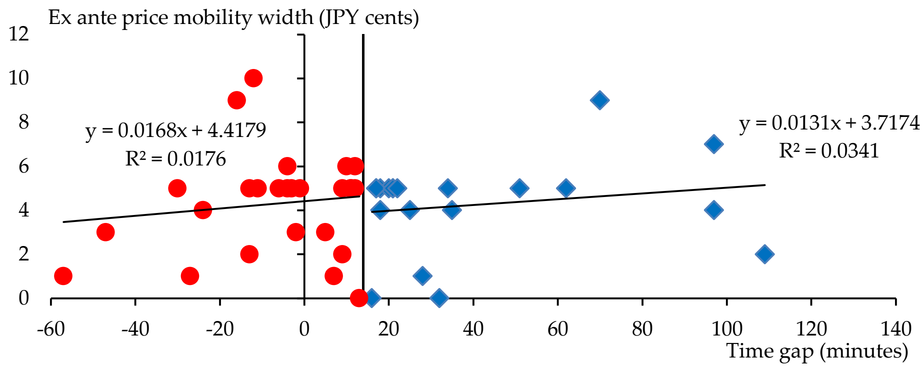
(a) Kuroda regime



(b) Shirakawa regime



(c) Fukui regime

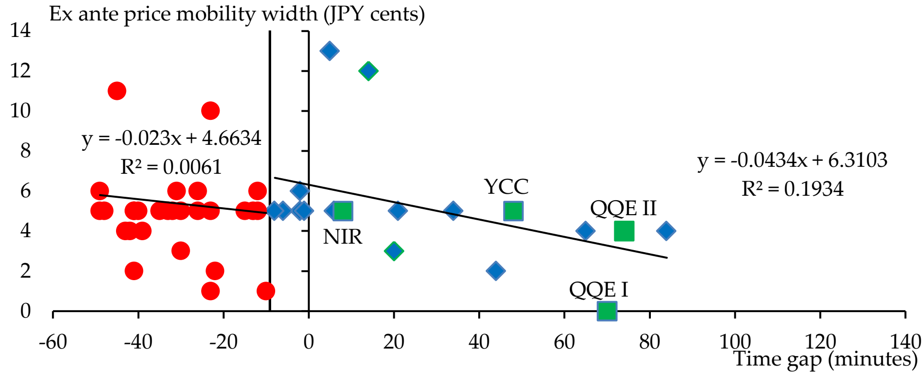


Notes 1. Dots correspond to policy announcements released before 15:00. The announcement on October 31, 2008 is excluded because of extraordinarily high mobility.

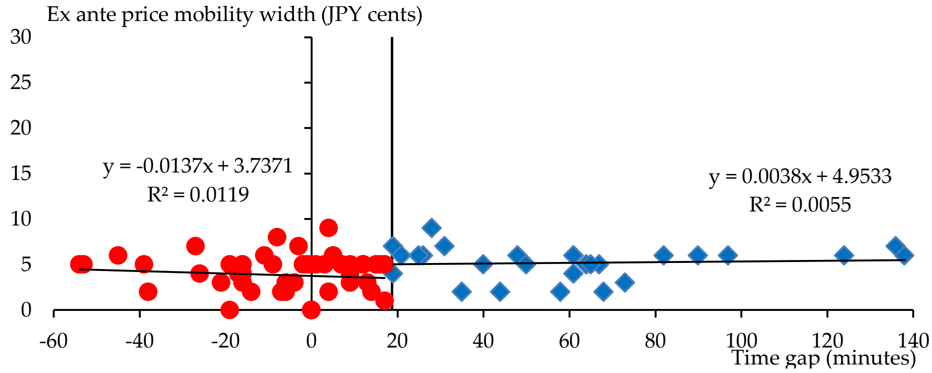
2. Vertical lines correspond to average time gap and divide samples under each regime.

Figure 14. Market Reaction to Policy Announcement Delays on the Short Side

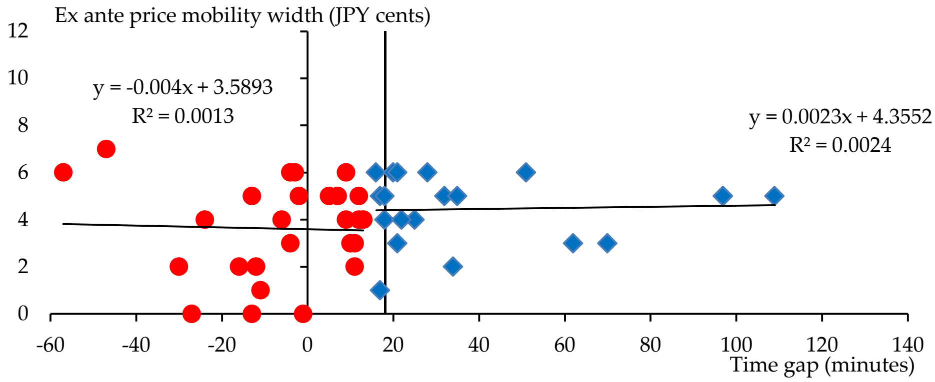
(a) Kuroda regime



(b) Shirakawa regime



(c) Fukui regime

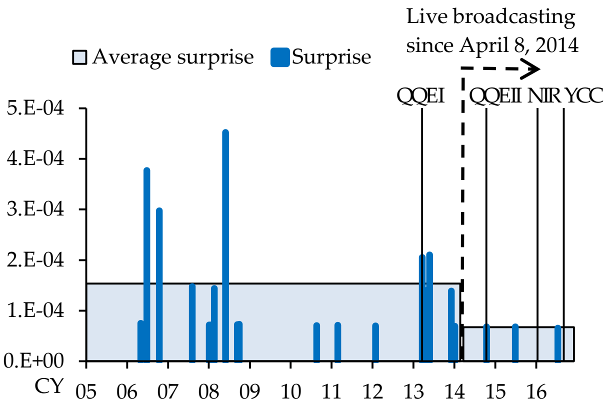


Notes 1. Dots correspond to policy announcements released before 15:00. The announcement on October 31, 2008 is excluded because of extraordinarily high mobility.

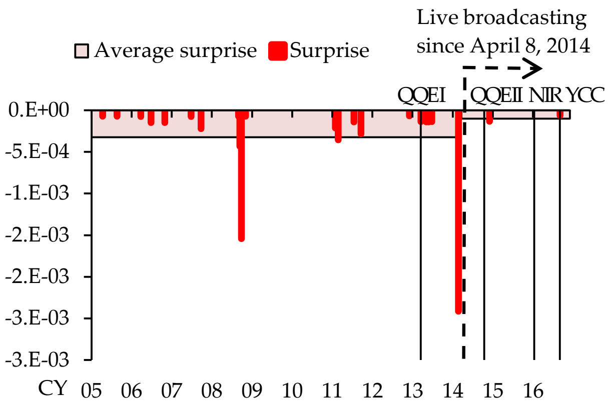
2. Vertical lines correspond to average time gap and divide samples under each regime.

Figure 15. Effects of Broadcasting Press Conference

(a) Low interest rates surprises



(b) High interest rates surprises

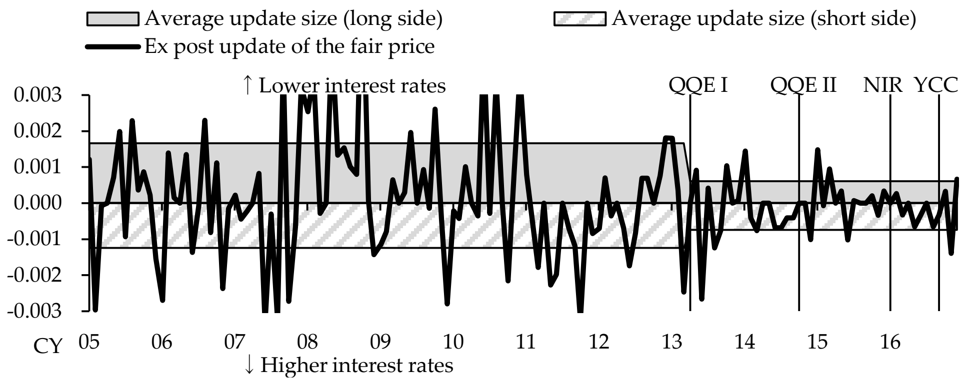


Notes 1. Surprises are quantified in the same way as in Figure 7 and summed at the interval between 15:30 and 17:30 on the policy announcement days. While the press conference is usually held from 15:30 through 16:30, the interval between 16:30 to 17:30 is included to capture ex post responses of traders.

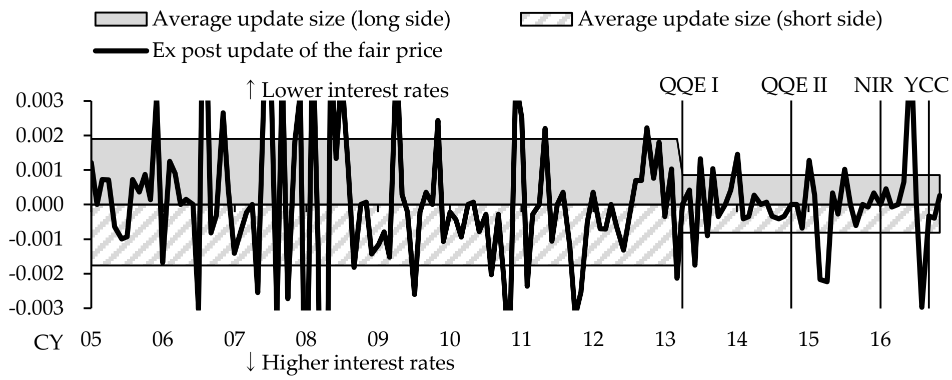
2. Average is taken over samples with non-zero surprises prior to April 8, 2014 and later, respectively.

Figure 16. Updates of the Fair Price in Reaction to Economic Indicators

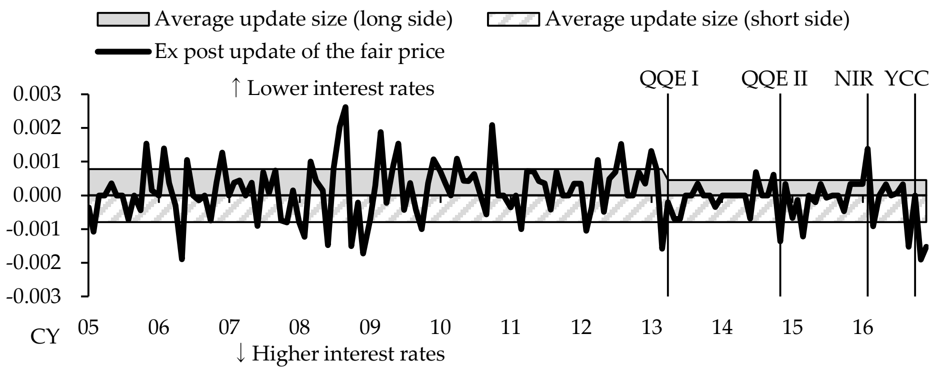
(a) Indices of Industrial Production



(b) Consumer Price Index



(c) Economic Watcher Survey

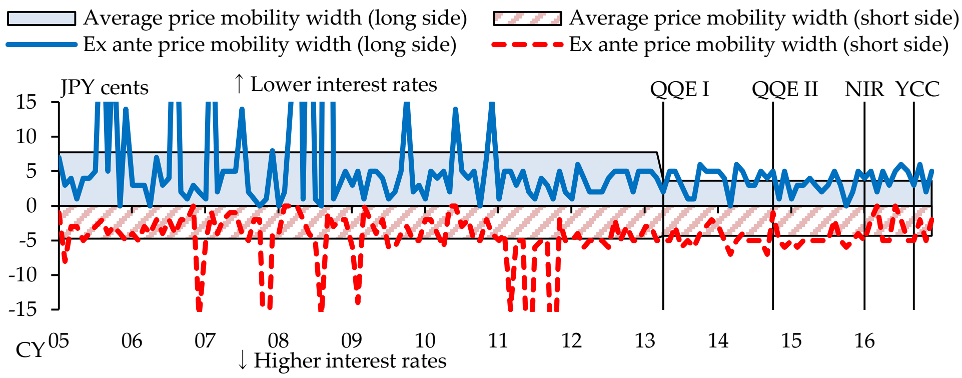


Notes 1. Ex post updates are given by log differences between ex ante fair price and the last fair price before the closing of the subsequent night session. In the case the indicators' release day coincides with the policy announcement day, update is replaced with zero.

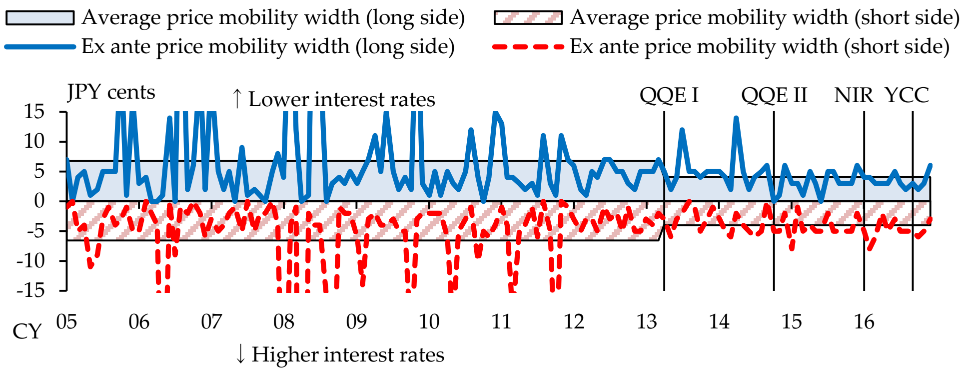
2. Average is taken over samples with non-zero update size prior to the introduction of QQE I (i.e., April 4, 2013), and later, respectively.

Figure 17. Traders' Expectations for Economic Indicators

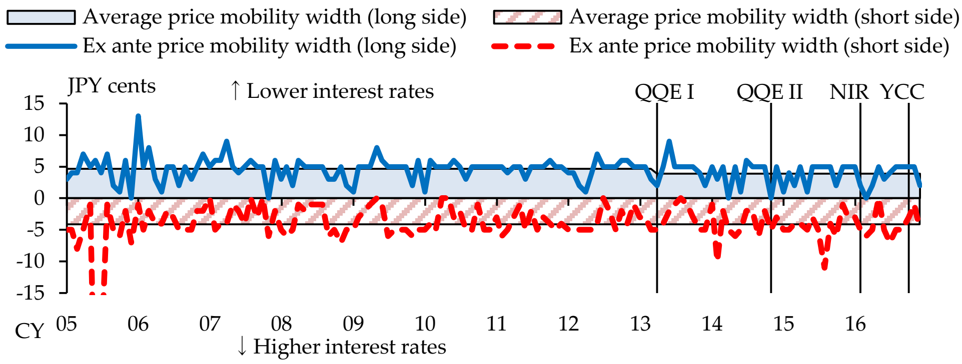
(a) Indices of Industrial Production



(b) Consumer Price Index



(c) Economic Watcher Survey

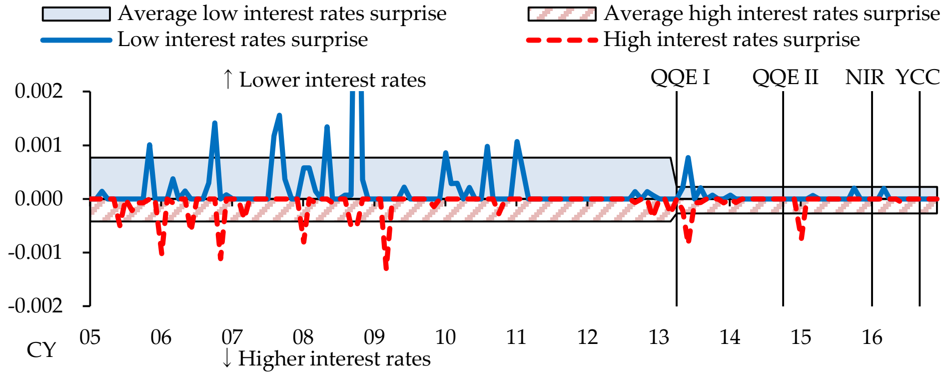


Notes 1. Ex ante price mobility width is given by $\overline{p}_{a\tau} - p_\tau$ for long side and $\underline{p}_{b\tau} - p_\tau$ for short side.

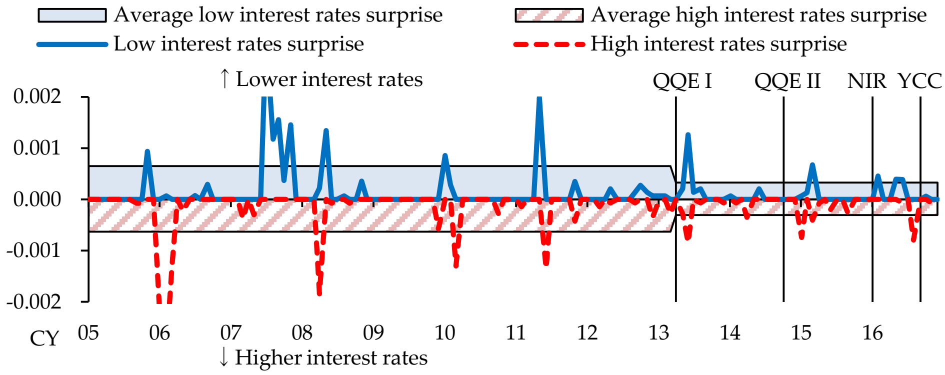
2. Average is taken over samples prior to the introduction of QQE I (i.e., April 4, 2013), and later, respectively.

Figure 18. Surprises Following Economic Indicators

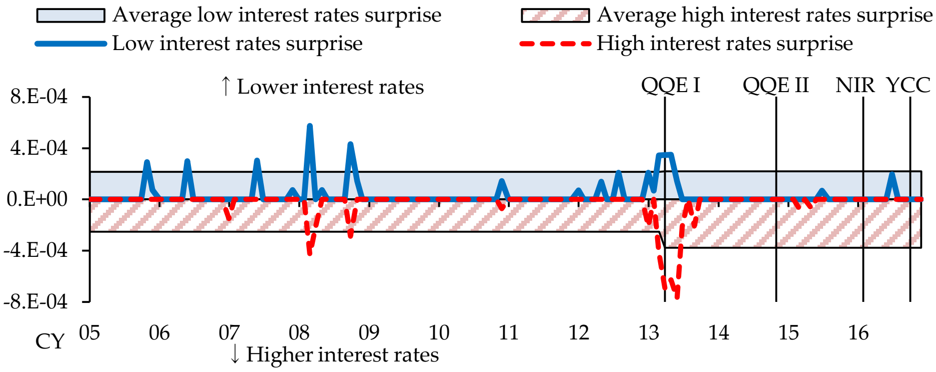
(a) Indices of Industrial Production



(b) Consumer Price Index



(c) Economic Watcher Survey

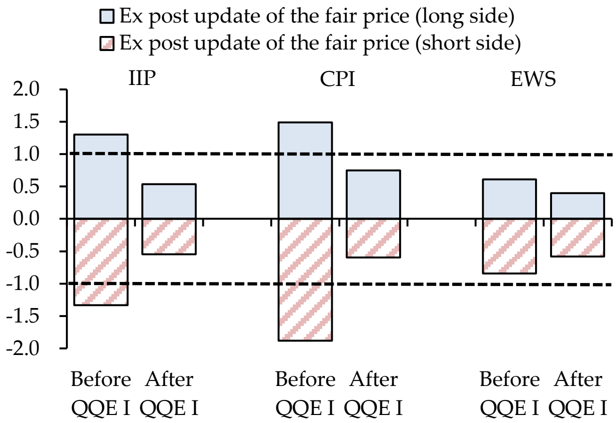


Notes 1. Surprises are quantified in the same way as in Figure 7 and summed at the intervals between the release and the closing of the subsequent night session. In the case the indicators' release day coincides with the policy announcement day, surprises are replaced with zero.

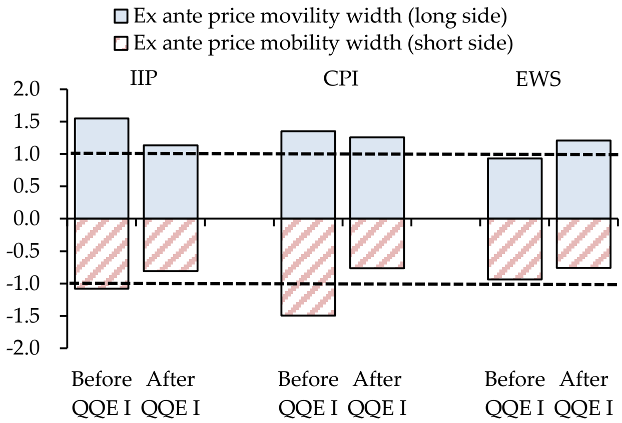
2. Average is taken over samples with non-zero surprises prior to the introduction of QQE I (i.e., April 4, 2013), and later, respectively.

Figure 19. Economic Indicators vs. Policy Announcements

(a) Fair price updates



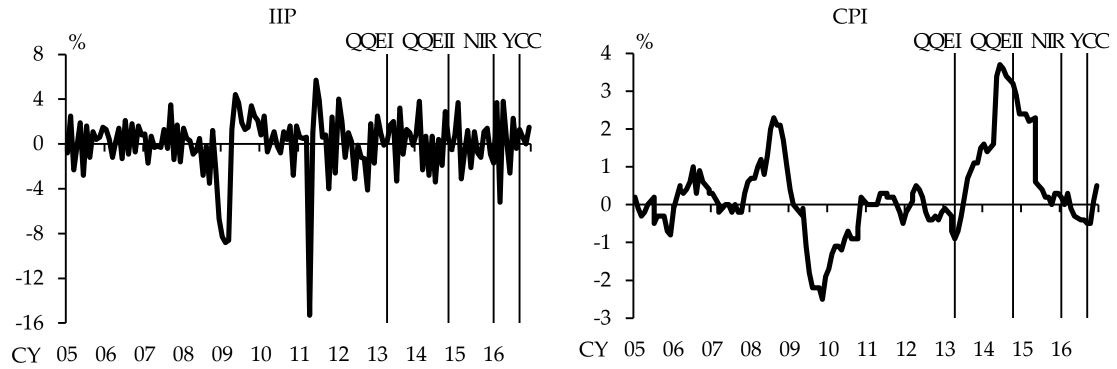
(b) Traders' expectations



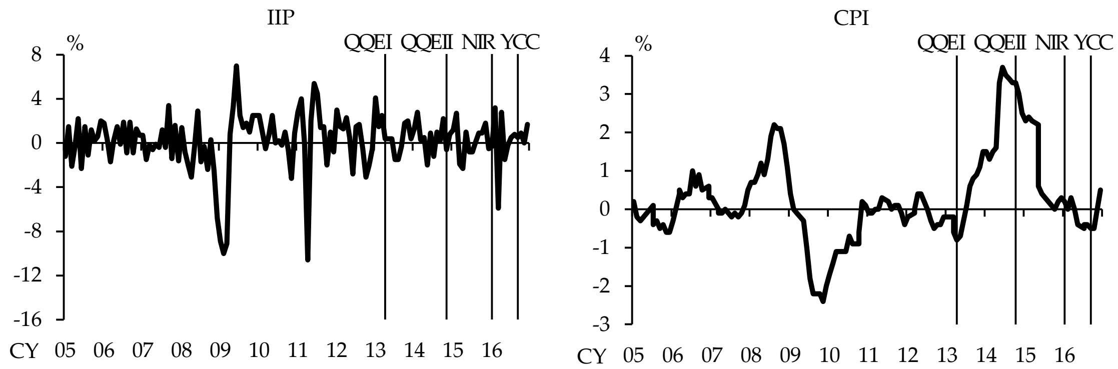
Note: Figures relative to those corresponding to policy announcements released before 15:00. Average is taken over samples prior to the introduction of QQE I (i.e., April 4, 2013), and later, respectively.

Figure 20. Economic Indicators and Forecasts by Analysts

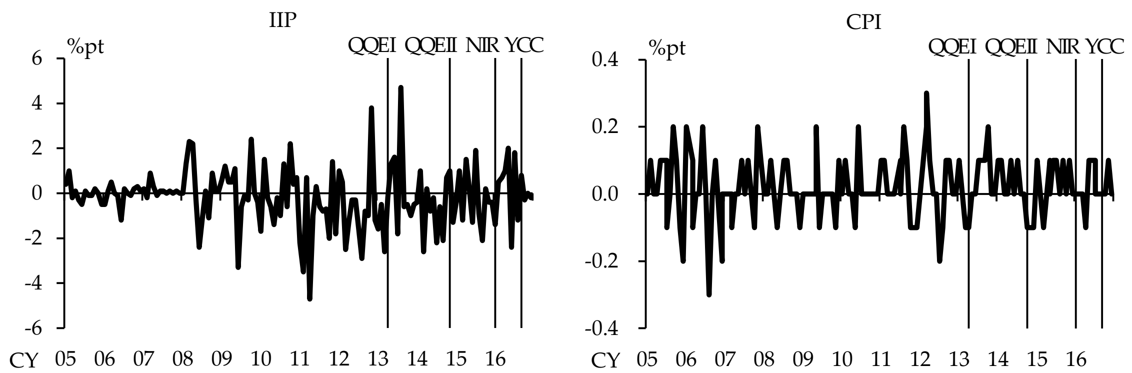
(a) Actual



(b) Forecasts



(c) Surprises

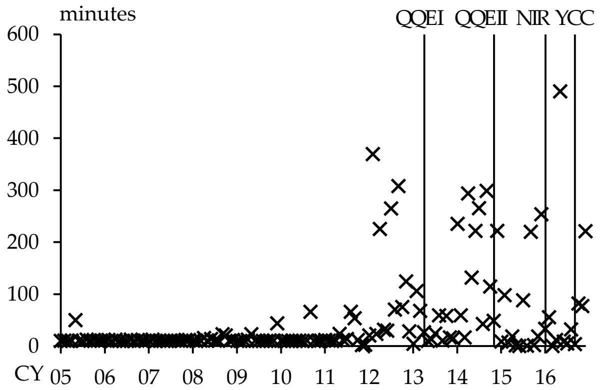


Note. Actual and forecasts are month-to-month change for CPI and year-to-year change for IIP, respectively. Surprises are given by subtracting forecasts from actual.

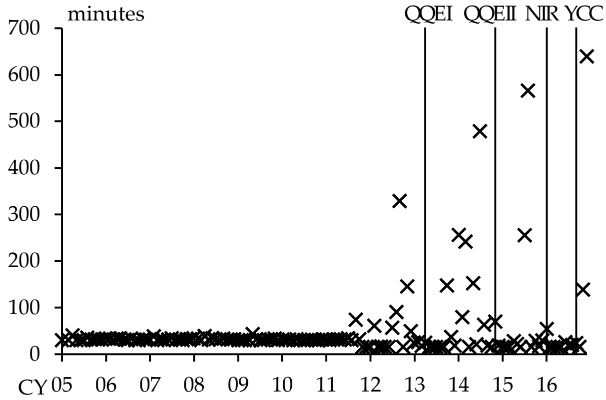
Source. Bloomberg.

Figure 21. Time to Responses to Economic News and Statements by the BOJ

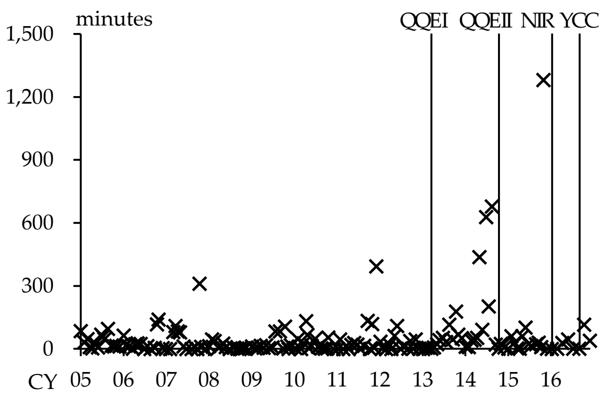
(a) Indices of Industrial Production



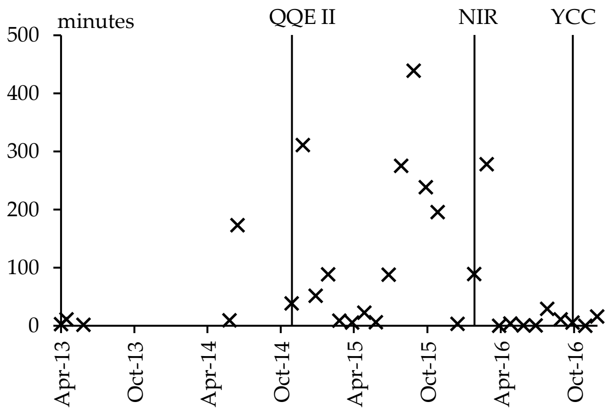
(b) Consumer Price Index



(c) Monetary Policy Meeting



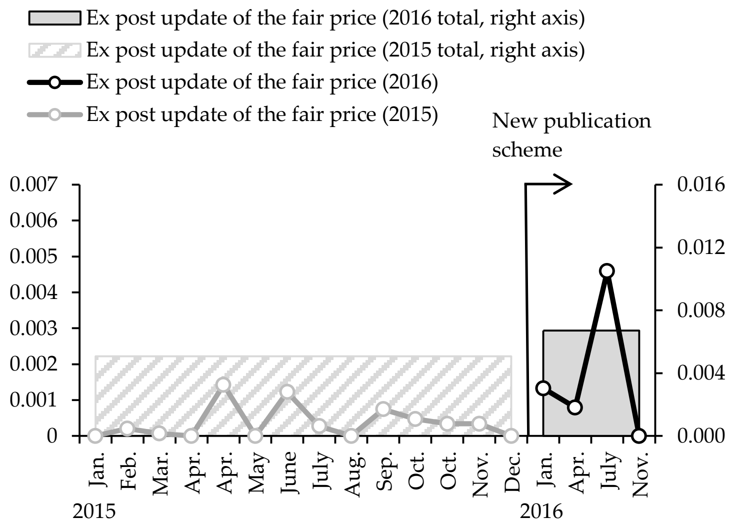
(d) Operation Schedule



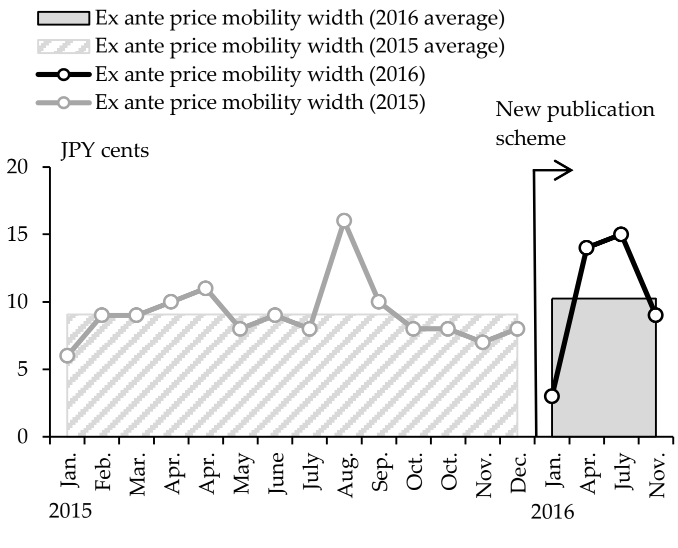
Note. Time gap between the news release and the first update of the fair price after the release. As for monetary policy meeting, the cases that the release comes after the closing of the night session are excluded from samples.

Figure 22. Total Information Value of BOJ's Economic Analysis: Fair Price Updates and Traders' Expectations of Economic Reports

(a) Updates of the fair price



(b) Traders' expectations



Notes 1. Ex post updates are on an absolute value basis. Ex ante price mobility width is total width on both long and short sides. Otherwise, computations are the same as in Figures 16 and 17.

2. Out of two Aprils and Octobers of 2015, the former and the latter correspond to the release of the Report and the Outlook, respectively.