Interbank Payment Timing is Still Closely Coupled

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Abstract

Within each day, participants in large-value payment systems have traditionally relied on incoming payments to make outgoing payments, generating a high degree of strategic complementarity in payment decisions. The conventional wisdom has been that such mutual dependence is no longer relevant in the era of large bank reserve balances at the central bank. Contrary to this conventional wisdom, we show through an empirical investigation of payments on Fedwire Funds that strategic complementarity still operates strongly. For each 1 percent incremental amount of incoming payments to a bank within a 15-minute interval, there is an estimated marginal increase in outgoing payments by that bank of 0.4 percent in the subsequent one-minute window. This relationship holds not only during stress periods, but also during normal times. Our findings shed light on bank balance-sheet constraints and the importance of ample reserves.

Keywords: Real-time gross settlement (RTGS) systems; Quantitative easing; Balance sheet management; Reserve balances

JEL: E42, E44, E52, E58, G21

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1 Introduction

We find that, even in the era of "ample" reserves, the amount of payments that a bank makes in a given minute depends significantly on the amount of payments it has received over preceding minutes, indicating a high degree of strategic complementarity. This "close coupling" of interbank payments suggests that banks act as though their intraday reserve balances are a scarce resource, even when total reserve balances in the U.S. banking system have been well over $1 trillion, far in excess of aggregate reserve balances before the Great Financial Crisis (GFC). This in turn suggests that there is still a potential for strategic cash hoarding when reserve balances get sufficiently low, as in mid-September 2019 and mid-March 2020, when large banks suddenly negotiated very high interest rates for providing overnight liquidity in the Treasury repo market.

We study the coupling of interbank payments in the Fedwire system, the primary large-value payment system operated in the United States by the Federal Reserve. In 2020, the Fedwire Funds Service (Fedwire) handled a daily payment value of over $3.3 trillion dollars, meaning that a sum equivalent to the (annual) GDP of the United States was turned over every 7 days or so.

In spite of the scale and speed of payments that go through large-value payment systems, the principles underpinning account-based payment systems have remained largely unchanged for centuries. A payment is made by debiting the account of the payer and crediting the account of the receiver. In the case of a wholesale payment system such as Fedwire, the system's participants hold balances at the Federal Reserve, but the book-keeping operations are in common with most other bank-railed payments. The sender of the payment must start with sufficient deposit balances to initiate a payment, or alternatively must borrow the needed amount (and then receive the loaned funds) or wait until other incoming payments replenish its deposit balance sufficiently to send the payment.

Before the GFC of 2008, banks in most jurisdictions maintained small reserve balances at the central bank compared to their outgoing payment volumes, and relied heavily on incoming payments in order to have sufficient deposit balances to make the outgoing payments. The reliance on incoming payments implied a high velocity of payments and a high degree of strategic complementarity among system participants, whereby the willingness to make payments promptly was greater when other system participants did so. Strategic complementarity gave rise to potential gridlock scenarios where a cautious stance of banks that waits for sufficient incoming payments before making an outgoing payment slows down the system as a whole. McAndrews and Potter (2002) studied the gridlock following the 9/11 attacks in 2001. Afonso and Shin (2011) provided a model calibrated for the Fedwire system to study the impact of liquidity hoarding on the functioning of the payment system. In order to avoid potential gridlocks, the Federal Reserve provides "daylight overdrafts," intraday loans to banks, that they can use to make outgoing payments in the expectation that positions would be squared before the end of the day.

These discussions of strategic complementaries faded from view after the GFC and the large expansion of bank reserve balances at the central bank in many jurisdictions associated with central bank asset purchase programs. The conventional wisdom has been that large reserve balances maintained by banks reduced or eliminated the reliance on incoming payments to make outgoing payments.

Perhaps surprisingly, this conventional wisdom turns out to be false. In an empirical investigation of the Fedwire system in the United States, we find that strategic complementarity of payments is alive and well. A 1-percent increment received in incoming payments by a bank in a 15-minute window predicts an additional 0.4 percent of outgoing payments in the subsequent one-minute window, even after we control for banks' balances at the beginning of the day. This effect holds during normal times that exclude stress periods, and so does not rely on special circumstances that put stresses on bank balance sheets. Instead, our results shed light on the shifting nature of bank balance sheet constraints in the era of ample reserves.

Our findings are especially notable given the contrary indications that came from the diminished role of daylight overdrafts in the real-time gross settlement (RTGS) system. Daylight overdrafts refer to the intra-day loans granted by the Federal Reserve to banks in the payment system so that they do can fulfill their payment obligations without waiting for incoming payments to replenish their reserve balances. Before the GFC, daylight overdrafts were used actively to oil the wheels of the wholesale payment systems and prevent gridlocks.

Figure 1 shows the peak daylight overdrafts in Fedwire over a long time span, going back to the 1990s. The left panel presents the value of peak daylight overdrafts both in dollar terms and as a proportion of total payments. We see the dramatic decline in peak daylight overdrafts in the regime of large reserve balances following the GFC of 2008. The right panel is a scatterplot of peak daylight overdrafts (y-axis) against excess reserves (x-axis), both normalized by total daily payment. The blue dots are for the pre-crisis period while the red dots are for the post-crisis period. The red dots show a strongly negative relationship between daylight overdrafts and excess reserves in the post-crisis period.

Taken at face value, the evidence in Figure 1 might give rise to the hypothesis that strategic complementarity in payments has been eliminated or greatly diminished. By contrast, we find that strategic complementarity, in the form of a positive reaction function mapping outgoing payments into incoming payments, remains a robust and consistent feature of the data. The system as a whole is less reliant on daylight overdrafts provided by the Federal Reserve, but the decisions of individual banks still reveal a strong hold of balance sheet constraints.

Uncovering the exact nature of these balance sheet constraints is beyond the scope of our paper,

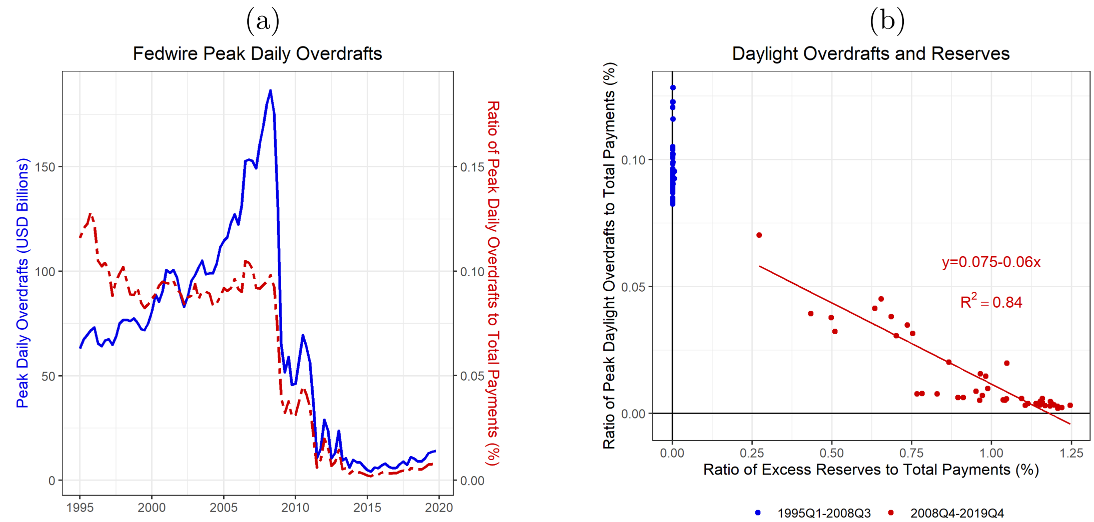

Figure 1: **Daylight overdrafts in Fedwire** - Peak daylight overdrafts (blue) and ratio of peak daylight overdrafts to total payments (dashed red) (a), and relationship between the ratio of peak daylight overdraft to total payments and excess reserves (b), 1995-2019. Source: Federal Reserve, FRED and Fedwire Funds Services.

but there are several important clues from the recent literature. Afonso, Cipriani, Copeland, Kovner, La Spada, and Martin (2021) and Correa, Du, and Liao (2020) discuss how reserves are deployed to repo lending or to supplying dollars in the FX swap market when spreads in these markets are unusually high. Banks do so by channeling the funds to their broker-dealer subsidiaries while keeping the overall size of the bank holding company's balance sheet unchanged. The fact that the overall balance sheet remains unchanged but that one class of liquid assets gives way to another suggests that banks are conscious of their overall Basel III leverage ratio. To the extent that the deviations from covered interest parity in the FX swap market are attributable to the same underlying forces constraining commercial bank balance sheets, bank balance sheet constraints will be the common thread tying the two, as discussed in Avdjiev, Du, Koch, and Shin (2019).

Copeland, Duffie, and Yang (2020) additionally point to the timing of payments for large Treasury security issuances, and to regulatory and supervisory liquidity requirements. For example, under post-GFC rules for resolution planning, commercial banks are required to have sufficient liquidity in a failure-resolution scenario to distribute reserve holdings across legal entities and across international units of the bank holding company. These requirements tie up reserves, exacerbating the strong hoarding incentives during times of stress in the short-term funding markets, as was the case in September 2019 and in the early weeks of the Covid-induced stresses in March 2020.

We find that the size of reserve balances is linked to the payment reaction function that we estimate. Consistent with the constraints highlighted in the literature above, we find that larger reserve balances are associated with a flatter payment reaction function, as one would expect given the reduced precautionary motive. We show that when reserve balances are relatively low, strategic complementarity strengthens: banks receive a higher fraction of their payments late in the afternoon as other banks delay payments to economize on intraday liquidity. Besides this quantitative variation, our key qualitative message is that the strategic complementarity of the payment decisions is alive and kicking. This strategic complementarity remains an important component of the overall approach to central bank balance sheet operations even in an environment of large amounts of reserves as demand for reserves have significantly changed since the GFC (Afonso, Giannone, La Spada, and Williams (2022)).

We begin with a brief introduction of the institutional details behind the Fedwire system in the United States and some stylized facts that are relevant to our study. The core of our analysis is the subsequent three sections of the paper, where we derive the empirical estimates of the reaction function of payment system participants, the relationship between participants' reaction function and their reserve balances, and how the reaction function has changed over time.

2 Data description

Our main dataset includes all payment transactions in Fedwire Funds Service (Fedwire Funds). Fedwire Funds is a real-time gross settlement system that settles transactions individually on an order-by-order basis, without netting. The system was developed in 1918 and is owned and operated by the Federal Reserve Banks. Participants, including banks, businesses and government agencies use Fedwire Funds to make same-day transfers in central bank money, that is, transfers between accounts held at the Fed. Fedwire Funds operates 21.5 hours each business day (Monday through Friday), from 9:00 pm Eastern Time (ET) on the preceding calendar day to 6:30 pm ET.[1] Settlement of funds is immediate, final, and irrevocable. As shown in Figure 2, daily instances and values of transfers have increased during the last decade, from around 500,000 daily transfers and $2.4 trillion on an average day in 2010 to more than 700,000 transfers with $3.3 trillion in daily value in 2020.

More than 5,000 participants sent or received Fedwire Funds transfers in 2020. We exclude from our sample master accounts of ancillary payment systems such as automated clearing houses (ACHs), other large value payment systems such as The Clearing House Inter-bank Payment System (CHIPS), settlement services such as Continuous Linked Settlement (CLS), and other "special" accounts including the Treasury General Account (TGA).[2] For computational convenience, we limit

[1] Operating hours were extended in December 1997 from ten hours to eighteen hours (12:30 am - 6:30 pm ET) and again in May 2004 to twenty-one and a half operating hours (9:00 pm - 6:30 pm ET). On March 8, 2021, the Fedwire Funds Service closing time was moved to 7:00 pm from 6:30 pm ET, expanding the operating hours to 22.

[2] We exclude entities that the National Information Center (NIC) entity type classifies as "Edge/Agreement Corporations" and "Domestic Entity Other," with the exception of the Federal Home Loan Banks. See https:

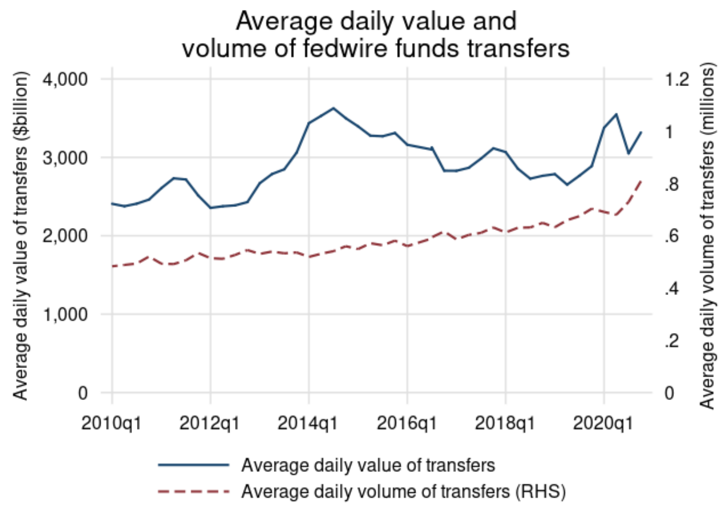

Figure 2: Fedwire Funds average daily value ($billion; blue) and average daily volume (millions of transactions; dashed red), 2010-2020. Source: Fedwire Funds Services.

our sample to the top 100 master accounts, ranked by the average daily total dollar value of payments sent in the first 100 business days in 2020. Payments in Fedwire Funds are highly concentrated. On an average day in our sample, the top 100 entities (master accounts) are responsible for 88% of the dollar value of all payments sent through Fedwire Funds, which is around $3 trillion per day.

We focus particularly on the 15 largest master accounts and study their payment activity to and from any entity in the top 100. These 15 largest master accounts correspond to national and state member banks, and branches and agencies of foreign banks, among other entity types. For simplcity, we refer to all of these as "banks." On an average day in our sample, these top 15 "banks" are responsible for 77% of the dollar value of all payments sent by the top 100 entities, which is about $2 trillion per day.

Our second dataset covers the reserve balances of depository institutions, including commercial banks, credit unions, and branches and agencies of foreign banks, based on internal Federal Reserve accounting records. We use daily reserve balances that capture end-of-day closing balances for each entity in our sample. In our analysis, we proxy opening balances by the preceding day closing balances. As shown in Figure 3, reserve balances are also concentrated with the largest 15 banks, as measured by the average daily total dollar value of payments sent. These 15 banks held around 42% of the reserves in the U.S. banking system.

`//www.ffiec.gov/npw/Help/InstitutionTypes` for a list of NIC institution types.

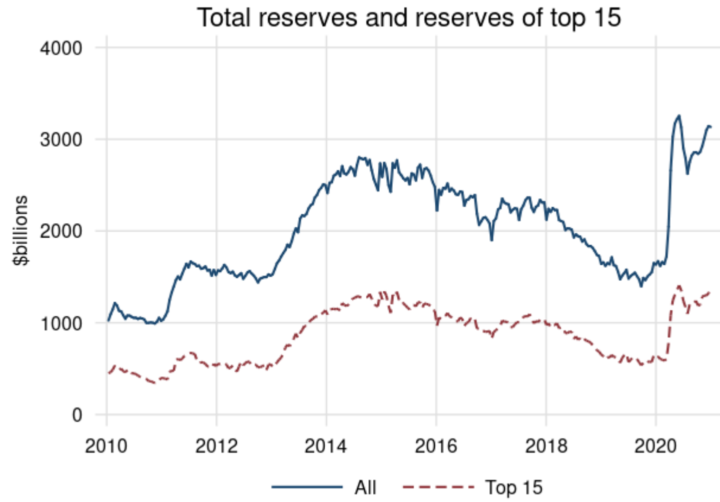

Figure 3: Aggregate reserve balances of U.S. depository institutions (blue) and of top 15 largest entities as defined by average daily total dollar value of payments sent (dashed red), 2010-2020. Source: Internal Federal Reserve accounting records and Fedwire Funds Services.

3 Strategic complementarity in payments

Prior to the financial crisis of 2007-2009, banks in the U.S. relied heavily on incoming funds to make their own payments (McAndrews and Potter (2002), Afonso and Shin (2011)). With the transition from an environment of scarce reserves to one of ample reserves, we can question whether strategic complementarities in payments still exist in real-time gross settlement (RTGS) systems such as Fedwire Funds.

To explore the question of complementarities in payments, we analyze the relationship between a bank's payments and its receipts for each minute in a business day. We focus our analysis on the top 15 most active banks as measured by their average daily total dollar value of payments during the first 100 business days in 2020, and study how the payments that a top bank makes in a one-minute interval correlate with its receipts over the previous 15 minutes.

The dollar value of payments in Fedwire Funds tends to follow a relatively predictable pattern over the course of a typical business day. As shown in Figure 4, there is almost no payment activity overnight. The dollar value takes off in the morning after 6:00 am and peaks in the late afternoon at around 5:00 pm, before the payment system closes at 6:30 pm ET. In all specifications, in addition to bank fixed effects and date fixed effects, we also include period-of-the-day fixed effects to control for these intraday payment dynamics. We include a dummy variable for payments that occurred in the first half hour of the business day, between 9:00 and 9:30 pm ET ("opening-of-day payments") as payments may be queued prior to the start of the business day to be processed once the day begins. We also include a dummy variable for payments sent between 9:30 pm and 6:00 am ET ("early payments") to capture the fact that few payments are processed overnight. We also include dummies for each half hour between 2:00 pm and 6:00 pm ET ("afternoon payments") and a dummy variable for payments between 6:00 and 6:30 pm ET ("end-of-day payments") to account for payment dynamics during the last half hour of the business day, when banks can only make settlement payment orders but not payments on behalf of customers.

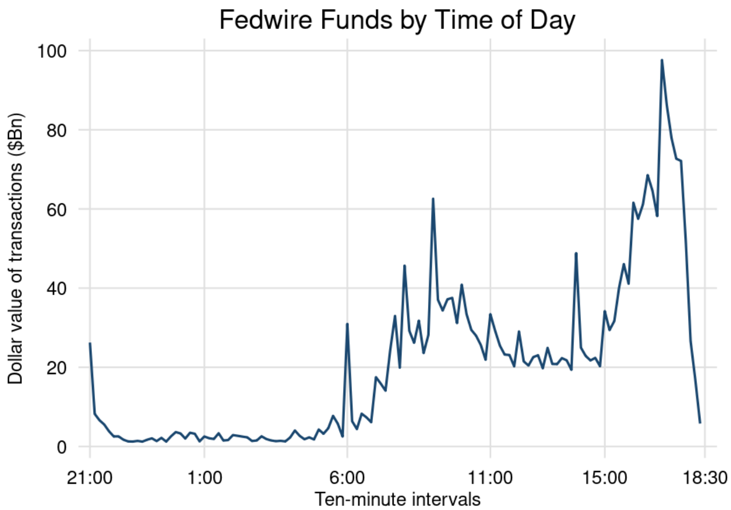

Figure 4: Daily dollar value of payments by time of the day, averaged over the first 100 days in 2020. Source: Fedwire Funds Services.

We estimate the following relationship between a bank's payments and its receipts:

$$\log\left(1 + P_{imt}\right) = \beta_0 + \beta_1 \log\left(1 + \sum_{s=m-15}^{m-1} R_{ist}\right) + \gamma_i + \gamma_t + \gamma_m^{open} + \gamma_m^{early} + \gamma_m^{afternoon} + \gamma_m^{eod} + u_{imt}, \quad (1)$$

where P_{imt} is the total dollar value of payments from bank i to its counterparties in minute m on day t; $\sum_{s=m-15}^{m-1} R_{ist}$ is the cumulative receipts of bank i during the previous 15 minutes; γ_i represents (sender) bank fixed effects; γ_t is date fixed effects; γ_m^{open} is an indicator variable equal to 1 between 9:00 pm and 9:30 pm ET on the preceding calendar day; γ_m^{early} is an indicator variable equal to 1 between 9:30 pm ET on the preceding calendar day and 6:00 am ET; $\gamma_m^{afternoon}$ are indicators variables for each 30 minutes between 2:00 pm and 6:00 pm ET; γ_m^{eod} is an indicator variable equal to 1 between 6:00 pm and 6:30 pm ET; and u_{imt} is an "error" term. In all regressions, standard errors are corrected for heteroscedasticity and clustered at the bank (sender) level. Value amounts are in US dollars (USD).

Table 2 summarizes the results. Column (1) presents the least-squares estimates of the coefficients of our baseline specification and shows the relation between a top-15 bank's payments over the next minute and its cumulative receipts in the previous 15 minutes, during the first 100 business days in 2020. The point estimate on cumulative receipts is positive (0.04), but not statistically different from zero. A key feature of the payments data is the presence of zeros, that is, minutes during which a bank does not make any payment. Overall, almost 45% of the observations in our dataset correspond to minutes when banks do not send payments. For comparison, column (2) shows our baseline relationship estimated only on minutes when banks make payments. The point estimate on cumulative receipts is now 0.119 with a standard error of 0.062, suggesting that a 1% increase in the cumulative payments that bank i receives in the previous 15 minutes translates into a 0.12% increase in the payments made by the bank over the next minute.

However, a linear model might not be well-suited to explain the relationship between payments and receipts. First, to isolate the strategic complementarity effect, we focus on high-frequency data. In particular, we use minute-by-minute data for each of the top 15 most active banks. Second, payments in Fedwire Funds are concentrated late in the day, as shown in Figure 4. And while the payment system is open for 21.5 hours each business day, payments sent before 6:00 am ET (which covers 40% of operating hours) represent less than 7% of the total daily value sent. As a result, our data are characterized by minutes during which banks do not make payments (the zero values), and minutes in which banks make payments that take on a wide range of values. In this case, the least squares estimators of the regression parameters will be biased and inconsistent. Instead, we estimate a Tobit model, which is able to capture the non-linearity in payments data.

Column (3) presents the results of the Tobit estimation. The point estimate on cumulative receipts is 0.575 with a standard error of 0.179. Since we are estimating a Tobit regression, the estimated coefficient cannot be directly interpreted as the marginal effect of a change in cumulative receipts on payments. To allow for that interpretation, the estimated coefficient can be adjusted by a scale factor that first captures the probability of observing whether a bank makes a (non-zero) payment in the next minute given its cumulative receipts (Wooldridge (2001)). The implied marginal effect is reported in column (4): A 1% increase in the cumulative payments received by bank i in the previous 15 minutes translates into a 0.4% increase in the value of payments that the bank makes over the next minute. This relationship is robust to double-clustering the standard errors at the bank and date level. (See column (2) in Table 2.)

These results show a strong positive and significant relationship between a bank's receipts and the payments made by the bank to its counterparties. We find this relationship during a period when total reserves in the banking system exceeded $2.5 trillion, suggesting that strategic complementarities in payments exist in economies with abundant reserves.

3.1 Robustness

Estimating complementarities directly is typically challenging because of omitted-variable concerns. All of our specifications include (i) bank fixed effects to control for unobserved factors that, while constant across days and minutes, vary across banks such as bank size; (ii) date fixed effects to take into account factors that vary only over time, such as days with a high or low daily payment volume; and (iii) period-of-the-day fixed effects to control for unobserved factors that vary across minutes, including the intraday payment dynamics shown in Figure 4.

Our analysis may also omit relevant variables that vary over time. For example, as the reserve balances that banks hold at the Federal Reserve increase, banks could rely more on these balances than on incoming payments to make outgoing payments. Omitting balances may affect the relationship between payments and receipts. To assess this effect, specification (3) includes the opening balance B_{it} of bank i on date t. As shown in Table 2, column (3), controlling for opening balances does not alter the relationship between a bank's recent receipts and the payments that it makes.

Our results could also be capturing a spurious relationship that might arise on days with high (or low) payment volume regardless of the existence of strategic complementarities in payments. All of our specifications include date fixed effects to capture unobserved factors such as days with high or low payment activity. In addition, to control for payment dynamics at the time when a bank sends out payments, we include in specification (4) each bank's cumulative payments that day up to 15 minutes prior. As shown in Table 2, column (4), there persists a positive and significant relationship between a bank's recent receipts and the payments that it makes, although the estimated magnitude of the effect is reduced. A 1% increase in the cumulative payments that a bank receives in the previous 15 minutes translates, with this specification, into a 0.2% increase in the payments that it makes over the next minute. Model (5) presents an alternative specification in which we control for the payments sent by the bank in the prior minute. Consistent with our previous finding, we still find a positive and significant relationship between a bank's recent receipts and the payments that it makes.

Our results show the relationship between the payments that a bank makes in a given minute and the payments that it has received in the previous 15 minutes. We selected these time windows for consistency with the original work of McAndrews and Potter (2002). We have also considered alternative specifications with different time periods for cumulative receipts and for payments made. The results are qualitatively the same. For instance, column (6) in Table 2 presents the result of estimating the relationship between payments made over the next minute and receipts in the previous 30 minutes. The marginal effect of a 1% increase in a bank's cumulative receipts now translates into a 0.6% increase in the payments it makes over the next minute. We also looked at the relation between receipts and payments made over time periods longer than 1 minute. Specification (7) shows that the relationship persists when based on the payments a bank makes to its counterparties over 5-minute windows.

Following the empirical approach in Chen, Goldstein, and Jiang (2010), we also explore differences in the level of strategic complementarities faced by banks. Banks face a higher degree of complementarity when aggregate balances in the banking system are low because they need to rely more on incoming funds to make their payments. Similarly, the degree of complementarity is lower on days in which aggregate balances are high, because banks may rely on their own balances to meet some payments and the benefit of coordinating their payments with other banks is reduced. We test for differences in the relationships between payments and past receipts for different levels of aggregate level of balances. Column (8) includes the interaction between a bank's cumulative receipts in the previous 15 minutes and aggregate opening balances for the same day. As shown in column (8), the relationship varies for different level of opening balances: On days with high aggregate opening balances, the link between payments and past receipts persists, but is dampened relative to days with low aggregate balances.

4 Complementarity and reserves

Section 3 finds complementarity in payments in 2020, consistent with the most active banks relying on incoming funds to make their payments in an environment of ample reserves. Banks' incentives to adjust the timing of their payments to match that of their receipts, creates conditions in which liquidity shocks can propagate through the U.S. payment system. These dynamics are especially important if adjustments in the timing of payments occur on days when reserve balances in the banking system are relatively low, because banks might also need to further adjust their liquidity management practices, reinforcing the strategic complementarity of payment timing.

In this section we explore in more detail the relationship between strategic complementarity in payment timing and the aggregate level of reserves in the banking system. Column (9) of Table 2 shows an estimate of the relationship between a bank's cumulative receipts in the previous 15 minutes and its payments over the next minute, allowing for an interaction term between the bank's cumulative receipts and aggregate reserves on that day. We find that a 1% increase in the cumulative payments translates into a 0.4% estimated increase in the payments it makes over the next minute, and that this effect is stronger when aggregate reserves are lower.

Next, we look at payment activity on days with high and low aggregate reserve balances to identify potential differences in the intraday timing of payments depending on the aggregate level of reserves. Figure 5 shows intraday payments received by the top 15 banks for days with high (blue) and low (dashed red) opening balances, as defined by the top and bottom deciles of the reserve balances distribution. These intraday receipts are aggregated over 20-minute periods, normalized by same-day total receipts and averaged over the first 100 business days in 2020. As shown in Figure

5, the average share of daily payments that banks receive in the morning is higher on days with high opening balances than on days with low opening balances.

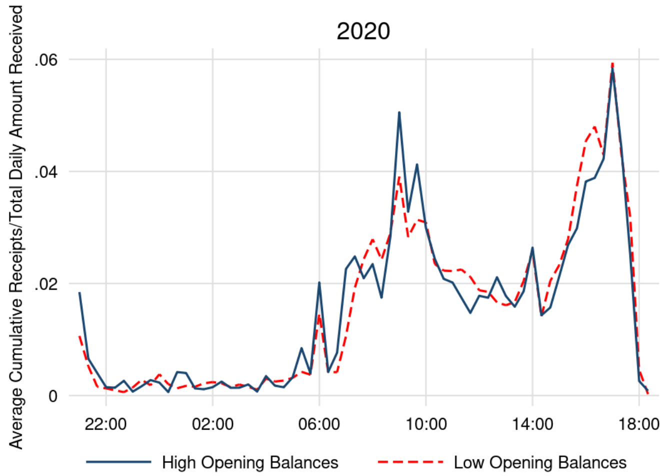

Figure 5: Share of daily payments received by the top 15 banks on top (blue) and bottom (dashed red) decile of days by opening balances, averaged over the first 100 days of 2020. Source: Internal Federal Reserve accounting records and Fedwire Funds Services.

In order to examine this issue more closely, we estimate the relationship between these shares of receipts during 20-minute periods throughout a business day and the level of reserve balances that day. For the first 100 business days in 2020, we aggregate the payments that the top 15 banks receive over 20-minute periods, normalize them by total receipts that day and regress them on time dummies for each of these 20-minute periods, and the interaction of these periods with the total opening balances of the top 15 banks. We are interested in understanding if the relationship between the share of receipts and the level of reserves changes throughout the day. We estimate the following OLS specification:

$$\frac{R_{st}}{R_t} = \beta_{1s} + \beta_{2s} B_t + u_{st}, \tag{2}$$

where R_{st} is the total dollar value of payments received by the top 15 banks in the 20-minute period s on day t; R_t is the total dollar value of payments received by the top 15 banks on day t; B_t is total opening balances of the top 15 banks on day t; and u_{st} is an error term. In all of these regressions, standard errors are corrected for heteroscedasticity. Quantity variables are measured in USD.

Figure 6 summarizes the estimation of equation (2). Panel (a) presents estimates of β_{1s} for each 20-minute period during the business day. Consistent with the timing of payments shown in Figure 5, panel (a) in Figure 6 shows that the share of payments processed overnight is relatively low. This share increases in the morning at around 6:00 am ET and then again in the afternoon, with the majority of receipts between 3:30 pm and 5:30 pm ET. Panel (b) presents estimates of β_{2s} and shows a positive (and statistically significant) relationship between the share of receipts and reserve balances in the morning and a negative one in the afternoon. On days with high reserve balances, banks receive a higher fraction of their receipts in the morning, rather than later in the afternoon.

(a) (b)

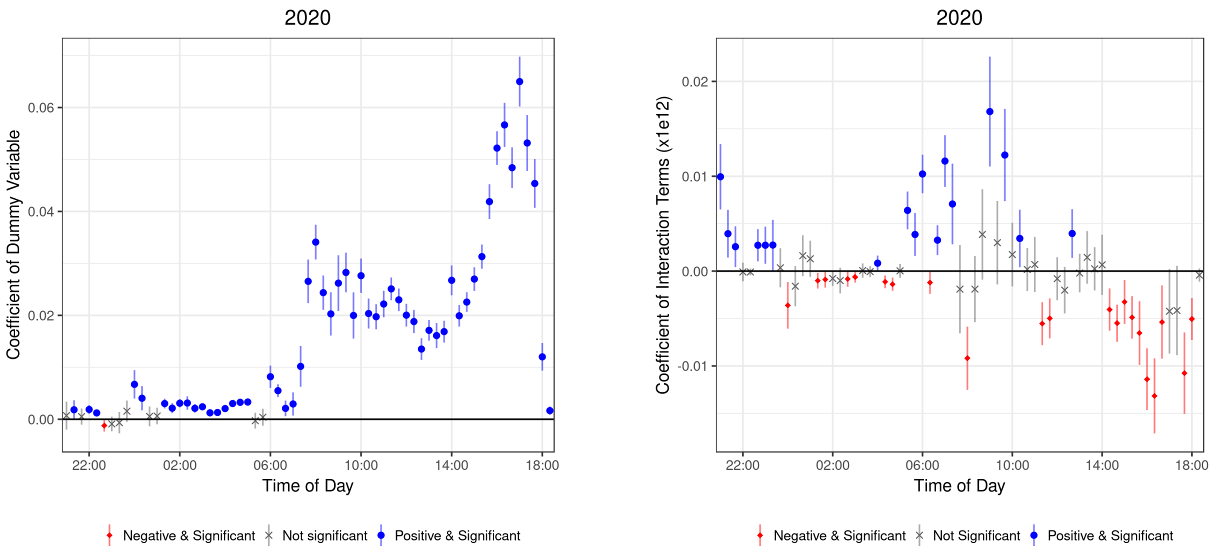

Figure 6: **Share of daily receipts and reserve balances** - Coefficient estimates $\hat{\beta}_{1s}$ (a) and $\hat{\beta}_{2s}$ (b) in equation (2) estimated over 20-minute periods for the top 15 banks during the first 100 days in 2020. Solid blue circles (red diamonds) denote a positive (negative) coefficient that is statistically different from zero at the 90% confidence level. The lengths of the bars correspond to 90% confidence intervals around point estimates. Source: Internal Federal Reserve accounting records and Fedwire Funds Services.

5 Strategic complementarity over time

Sections 3 and 4 show that, in 2020, top banks react in the timing of their payments to the timing chosen by other banks, and that this relationship changes with the level of aggregate reserves. In this section, we look at the evolution of this relationship since 2010. We first estimate the relationship between the payments made by a bank over one-minute intervals and the payments that it received in the previous 15 minutes, using the baseline specification in equation (1). We estimate quarterly Tobit regressions for the top 15 most active banks as measured by their average total dollar value of payments in each quarter over 2010-2020. Figure 7 shows the Tobit coefficient for each quarter in our sample (blue), as well as the time evolution of the total reserves balances held by these top 15 most active banks (dashed red).

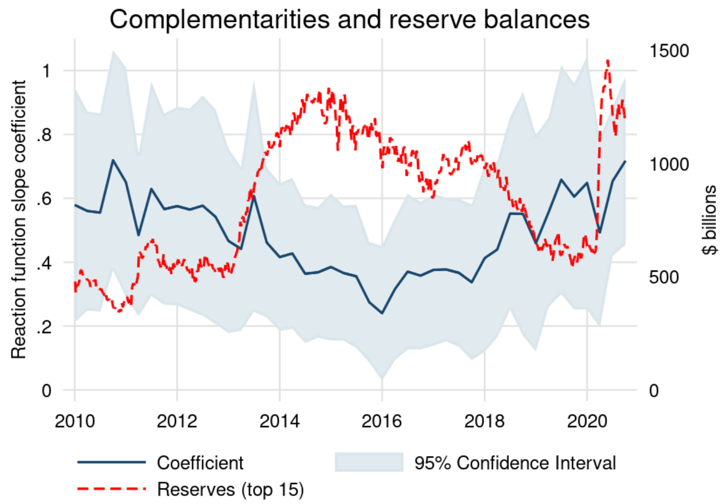

Figure 7: **Complementarities and reserve balances** - Quarterly Tobit coefficient estimates $\hat{\beta}_1$ (in equation (1)) and reserve balances of top 15 largest entities as defined by average daily total dollar value of payments sent (dashed red), 2010-2020. Source: Internal Federal Reserve accounting records and Fedwire Funds Services.

As shown in Figure 7, the synchronization of payments is not just a feature of payments dynamics in 2020, but has been present since 2010. The evolution of this reactive approach to payment timing seems to mirror that of reserve balances, with coordination being higher when reserve balances are lower. Figure 8 displays the average share of payments received by time of the day on days with high (blue) and low (dashed red) opening balances, as defined by the top and bottom deciles of the reserve balances distribution. On days with low reserve balances, banks coordinate their payments more, adjusting their timing. On these days, banks receive a higher share of their daily payments later in the day.

Figure 9 summarizes the estimated relationship between the share of receipts and the level of reserves over 20-minute periods from 2010 to 2020 (equation (2)). The estimated coefficients $\hat{\beta}_{2s}$ in panel (b) show that on days with higher opening balances, a higher share of the daily payments is sent earlier in the day (in the morning).

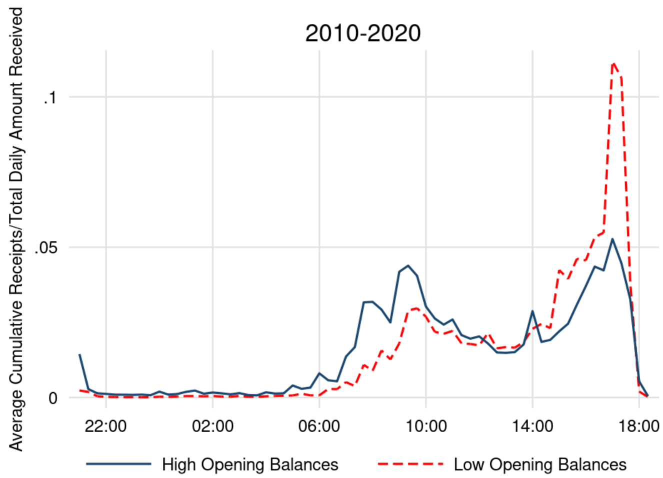

Figure 8: Share of daily payments received by the top 15 banks on top (blue) and bottom (dashed red) decile of days by opening balances, averaged over 2010-2020. Source: Internal Federal Reserve accounting records and Fedwire Funds Services.

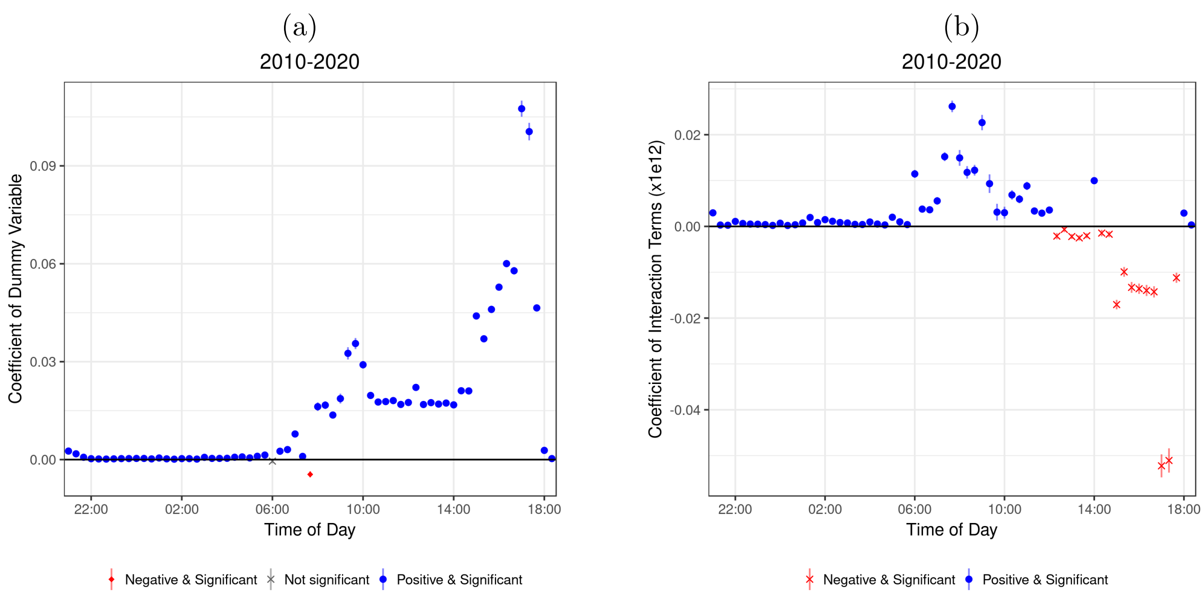

Figure 9: **Share of daily receipts and reserve balances -** Estimates of $\hat{\beta}_{1s}$ (a) and $\hat{\beta}_{2s}$ (b) over 20-min. periods for the top 15 banks during 2010-2020. Solid blue circles (red diamonds) denote a positive (negative) coefficient that is statistically different from zero at the 90% confidence level. The lengths of the bars correspond to 90% confidence intervals around point estimates. Source: Internal Federal Reserve accounting records and Fedwire Funds Services.

6 Concluding remarks

Even in the era of ample reserves, the payment decisions by banks in the wholesale RTGS system display the tell-tale signs of banks placing a non-negligible value on reserves held at the central bank. Uncovering the underlying economic reasons for the apparent non-zero value of reserves is an important topic of future investigation.

In this paper, we find evidence that banks in the U.S. still economize in the use of intraday liquidity and rely on incoming payments to make outgoing payments, generating a high degree of strategic complementarity in payment decisions. These results persist amid reserves balances in the banking system well in excess of the aggregate balances prior to the Great Financial Crisis and shed light into the discussion on the shifting nature of banks' demand for reserves and balance sheet constraints in the era of ample reserves. As central banks around the world move ahead in tightening their monetary stance and shrinking their balance sheets in this process of monetary tightening, the potential consequences of draining of reserves on the wholesale payment system will be an important input into the policy process.

Our findings also show that the strength of this strategic complementarity varies with the level of aggregate reserves and becomes stronger as reserves decline. This suggests that there is a potential for strategic cash hoarding when reserve balances get sufficiently low, as it was the case in mid-September 2019 and mid-March 2020. The shift in business models of banks where reserve balances have increasingly been used to finance short-term funding operations will be a promising avenue for further study. To the extent that reserve balances have been the marginal source of funding in FX swap markets and other short-term funding markets, the shrinking of reserve balances will also hold potentially important implications for market functioning and financial stability.

Table 1: **Bank payments and receipts.** - The dependent variable is the logarithm of (1 plus) the total dollar value of bank i's payments to its counterparties in minute m of day t, P_{imt}. $\sum_{s=m-15}^{m-1} R_{ist}$ is bank i's cumulative receipts during the previous 15 minute. In columns (1) and (2), we estimate a linear model using OLS. In column (3), we estimate a Tobit regression. Standard errors are corrected for heteroscedasticity, clustered at the bank (sender) level. Variables are in USD. Specifications are run in logs. Sample includes payments of top 15 most active banks during the first 100 business days in 2020.

	$\log(1+P_{imt})$			
	Linear (OLS)		Tobit (MLE)	
	(1)	(2)	(3)	(4)
	$y \geq 0$	$y > 0$	Coefficient	Marginal
$\log(1+\sum_{s=m-15}^{m-1} R_{ist})$	0.040	0.119*	0.575***	0.395
	(0.083)	(0.062)	(0.179)	
Clustering	Bank	Bank	Bank	
Bank FEs	Y	Y	Y	
Date FEs	Y	Y	Y	
Early dummy	Y	Y	Y	
EOD dummy	Y	Y	Y	
Afternoon dummies	Y	Y	Y	
Open dummy	Y	Y	Y	
N	1,935,000	1,059,902	1,935,000	
Left-censored			875,098	
R^2	0.597	0.355		
Pseudo R^2			0.228	
Log-likelihood			-3,157,609.4	

Table 2: **Bank payments and receipts. Robustness -** The dependent variable is the logarithm of (1 plus) the total dollar value of bank i's payments to its counterparties in minute m of day t, P_{imt}. $\sum_{s=m-15}^{m-1} R_{ist}$ is bank i's cumulative receipts during the previous 15 minute, and B_{it} its opening balance on day t. We estimate a Tobit regression. Standard errors are corrected for heteroscedasticity, clustered at the bank (sender) level in specifications (1) and (3)-(9), and double-clustered at the bank and date level in specification (2). Variables are in USD. Specifications are run in logs. Sample includes payments of top 15 most active banks during the first 100 business days in 2020.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	$\log(1+P_{imt})$	$\log(1+P_{imt})$	$\log(1+P_{imt})$	$\log(1+P_{imt})$	$\log(1+P_{imt})$	$\log(1+P_{imt})$	$\log(1+\sum_{s=m}^{m+4} P_{ist})$	$\log(1+P_{imt})$	$\log(1+P_{imt})$
$\log(1+\sum_{s=m-15}^{m-1} R_{ist})$	0.575***	0.575***	0.575***	0.302***	0.340***		0.519***	2.891**	3.131**
	(0.179)	(0.019)	(0.179)	(0.117)	(0.086)		(0.145)	(1.147)	(1.323)
$\log(1+\sum_{s=m-30}^{m-1} R_{ist})$						0.842***			
						(0.306)			
$\log B_{it}$			0.089*						
			(0.050)						
$\log(1+\sum_{s=1}^{m-16} P_{ist})$				0.899***					
				(0.121)					
$\log(1+P_{im-1t})$					0.681***				
					(0.065)				
$\log B_t$								1.474	
								(1.117)	
$\log B_t \log(1+\sum_{s=m-15}^{m-1} R_{ist})$								-0.194*	
								(0.105)	
$\log \text{Reserves}_t$									1.573
									(1.228)
$\log \text{Reserves}_t \log(1+\sum_{s=m-15}^{m-1} R_{ist})$									-0.207*
									(0.117)
Marginal effect of receipts	.395	.395	.395	.189	.257	.57	.469	1.99	2.15
Clustering	Bank	Bank × Day	Bank	Bank	Bank	Bank	Bank	Bank	Bank
Bank FEs	Y	Y	Y	Y	Y	Y	Y	Y	Y
Date FEs	Y	Y	Y	Y	Y	Y	Y	Y	Y
Half-Hour dummies	N	N	N	N	N	N	N		
Early dummy	Y	Y	Y	Y	Y	Y	Y	Y	Y
EOD dummy	Y	Y	Y	Y	Y	Y	Y	Y	Y
Afternoon dummies	Y	Y	Y	Y	Y	Y	Y	Y	Y
Open dummy	Y	Y	Y	Y	Y	Y	Y	Y	Y
N	1,935,000	1,935,000	1,935,000	1,935,000	1,935,000	1,935,000	1,935,000	1,935,000	1,935,000
Left-censored	875,098	875,098	875,098	875,098	875,098	875,098	656,455	875,098	875,098
Pseudo R^2	0.228	0.228	0.228	0.258	0.277	0.230	0.214	0.228	0.228
Log-likelihood	-3,157,609.4	-3,157,609.4	-3,157,589.8	-3,033,693.7	-2,956,649.9	-3,149,403.5	-3,639,043.4	-3,157,472.7	-3,157,482.9

Values are log dollars. Sample is top 15 entities by average daily payment value in first 100 days of 2020.

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