

LIQUIDITY EFFECTS OF THE EVENTS OF SEPTEMBER 11, 2001

- On September 11, banks experienced difficulties in making their payments because of widespread damage to property and communications systems in Lower Manhattan. As a result, other banks received fewer payments than were expected.
- Since banks rely heavily on incoming funds to make their own payments, the normal coordination of payments broke down, and liquidity shortages developed at many banks.
- The Federal Reserve responded by supplying abundant liquidity to the banking system through discount window loans and open market operations—actions that helped restore payments coordination.
- The episode highlighted the usefulness of the discount window and of intraday lending by the central bank as tools for managing marketwide demands for liquidity.

In the wake of the terrorist attacks of September 11, 2001, the Federal Reserve supplied funds to the banking system in unprecedented amounts. The destructive force of the attacks themselves caused severe disruptions to the U.S. banking system, particularly in banks' abilities to send payments. The physical disruptions caused by the attacks included outages of telephone switching equipment in Lower Manhattan's financial district, impaired records processing and communications systems at individual banks, the evacuation of buildings that were the sites for the payments operations of large banks, and the suspended delivery of checks by air couriers.

These disruptions left some banks unable to execute payments to other banks through the Federal Reserve System's large-value payments system, Fedwire, which in turn resulted in an unexpected shortfall for other banks. Banks rely heavily on incoming funds to make their payments, so these unexpected shortfalls affected the distribution of balances across the banking system. The disruptions to the communications infrastructure also made it harder for banks to redistribute balances across the banking system in a timely manner. Accordingly, the actions of the Federal Reserve System were intended to counteract the effects of the unusual distribution of liquidity and the difficulties experienced by the banking system in distributing liquidity directly.

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The direct effects of the unusual distribution of balances and the difficulty of redistributing them resulted in a less regular flow of payments by banks to other banks. A disrupted and thus less coordinated payments flow can be thought of as a sudden drop in the velocity of high-powered money—that is, balances at the Federal Reserve. In the U.S. fractional reserve banking system, banks in aggregate regularly make payments that exceed their deposits at the Federal Reserve Banks by a factor of more than 100. To attain such a highly efficient utilization of balances requires a robust interbank money market as well as intricately harmonized timing and regularity in banks' payments activity. The sudden disorder in the regular timing of incoming payments made planning for a bank's liquidity needs more difficult. While some banks that experienced technological difficulties in sending payments accumulated higher-than-desired balances, other banks' increased uncertainty (regarding which payments they might receive later in the day) led them to have higher precautionary demand for liquid balances. Consequently, the sources of liquidity internal to the banking system were not available or capable of addressing the widespread demand for liquidity.

The demand for such large amounts of liquidity by U.S. banks in this episode might seem somewhat puzzling at first glance. Typically, students of banking history point to bank runs as examples of extraordinary demand for liquidity. However, there were no runs on banks in the United States following September 11. Nor were there extraordinary demands for currency by banks or by the public. Furthermore, the incident that triggered the liquidity shortfall was well known to all market participants and was not generally believed to cause any bank's credit quality or solvency to deteriorate significantly. Instead, the events drew further attention to the high level of interdependencies present in payments flows.

Given these interdependencies, the provision of liquidity by the Federal Reserve System allowed banks to make payments while being assured that funds would be available at the end of the day. This assurance helped banks resume their normal payments activities, which in turn increased the circulation of liquidity through the normal channels. In addition, in the aftermath of the attacks, banks and their customers engaged in extraordinary cooperative efforts to overcome the problems caused by the destruction of infrastructure and its attendant effects. (A review of many of these efforts is provided in Federal Reserve Bank of New York [2002].)

In this article, we provide new evidence of the importance of the coordination mechanism that banks use in their normal payments activity to provide liquidity. We do so by first outlining the sources of funding for banks' payments activity,

thus highlighting the role of expected incoming payments from other banks. Next, we examine the disruptions in the payments and communications mechanisms on September 11 and the disorder that resulted from those disruptions. We then directly estimate banks' payments reactions to the receipt of payments from other banks and how their reactions changed in the days following the attacks. Finally, we discuss possible alternative ways to avoid such large disruptions to the payments mechanism, as well as ways to settle payments and the potential of these ways to reduce liquidity demands in the event of a significant disruption to the payments mechanism.

SOURCES OF LIQUIDITY FOR PAYMENTS: THE STRATEGIC DIMENSION

Banks must have enough liquidity to cover the amount of their payments made over Fedwire.¹ This liquidity typically consists of: 1) balances maintained on account with the central bank, 2) borrowing from other banks through the money markets, 3) credit extensions from the central bank, and 4) expected incoming transfers from other banks.² The last category creates a strategic challenge for banks in their liquidity management: they each rely on one another's payments as a source of funding.

The first source of funds available for making a payment is the balances kept on account at Federal Reserve Banks. For commercial banks, these balances consist of either required reserve balances, excess reserve balances, or service-related balances.³ These balances and service-related balances for August 2001 averaged \$14.65 billion per day.⁴ Banks are required to maintain these balances at a certain level during two-week periods known as reserve maintenance periods. In addition, the Federal Reserve can supply funds to the banking market through open market operations. By purchasing securities, the Federal Reserve directly increases banks' balances held on account at System Banks.

Overnight balances at the Federal Reserve are costly to maintain because they do not earn interest.⁵ Nevertheless, if banks' balances fall below the target on average for the two-week period, the banks face a penalty rate and must hold a higher level of balances during the next two-week period. In addition, if banks fall into overdraft positions on any given night, they must pay a substantial penalty of 4 percentage points in excess of the effective federal funds rate for that day. As a result of these disincentives to falling short of required balances and to holding excessive balances, banks try to target their overnight balances within a narrow band.

If a bank's payments over the course of the day exceed its receipts by more than the value of the balances with which it started the day, a bank can borrow funds in the federal funds market. Federal funds activity averaged \$144 billion per day in the first quarter of 1998 (Furfine 1999).⁶ Fed funds activity redistributes the liquidity among banks but does not add to the approximately \$15 billion in deposits in the Federal Reserve System. The Federal Reserve can increase the deposit level by lending funds through the discount window,⁷ where borrowing averaged only \$174 million per day in August 2001.⁸ Using the fed funds market and the discount window as sources of funding comes at a cost. Fed funds purchases are uncollateralized borrowing from other commercial banks, and the borrower pays the going fed funds rate to compensate the lender for the risk involved. Loans from the discount window are made at the discount rate, which is generally lower than the fed funds target rate. However, banks are not expected to rely on the discount window for funds on a regular basis.⁹

Intraday credit from the Federal Reserve System provides another source of funding for banks' payments.¹⁰ Coleman (2002) reports that the average value of daylight overdrafts, as this form of intraday credit is called, was \$32.8 billion per day in August 2001. However, banks tend to economize on this source of funding because the Federal Reserve System charges banks a fee for daylight overdrafts above a certain amount.

In general, the daily value of banks' payments greatly exceeds the value of those sources of liquidity. Consider that during August 2001, the value of Fedwire funds transfers averaged more than \$1.6 trillion per day, while banks held about \$15 billion on account.¹¹ In other words, the "turnover" of each dollar on banks' balances was more than 100 (if security transfers are included, the turnover ratio is about 180).¹² Banks can make payments even though the value of those payments is considerably higher than the value of the sources of funds because most payments are offset over the course of the day. Most banks can expect that they will receive a certain value of incoming payments during the day. To some extent, a bank can use these expected receipts to plan its submission of payments over Fedwire throughout the day. Of course, other banks are planning to use incoming funds to make payments as well, so how can banks in aggregate use expected receipts as a source of funding?

THE STRATEGY OF PAYMENTS COORDINATION

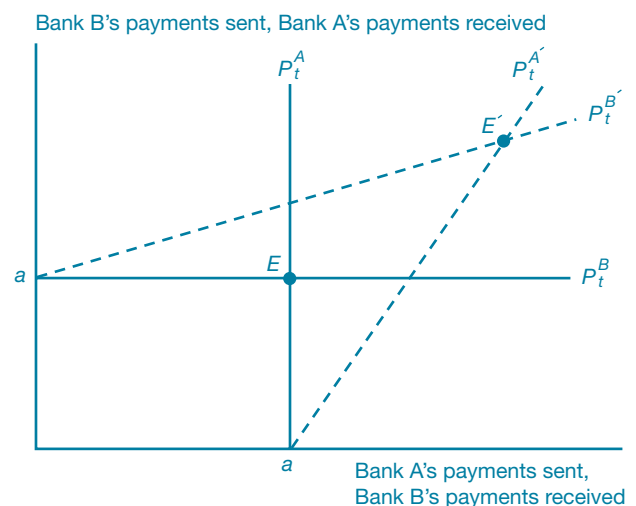
Banks use their scarce liquidity to serve both their customers' payments needs and to complete their own agreed-upon

payments arising from trading activities and interbank lending. As we noted, banks attempt to make use of incoming funds received from other banks by strategically timing payments.¹³ In models of this strategic payments behavior, banks make payments in reaction to their receipts from other banks. Each bank behaves by choosing the best reaction available to it, given its receipts. A bank's "reaction function" describes how a bank responds to payments received.

In general, we can identify at least two ways in which the receipt of a payment by a bank can increase the likelihood of that bank making a payment. First, the receipt of the funds replenishes the bank's balances at the central bank. Given that the bank has a list of payments it wishes to make during the day, the receipt of funds allows the bank to make an outgoing payment with less chance of incurring an overdraft in its account, all else being equal. In other words, some payments activity can be "self-funded" by matching outgoing payments to incoming payments. Second, as a payment is received on behalf of a customer, that customer is subsequently more creditworthy. If the customer had been at its credit limit prior to the receipt of payment, the receipt into its account relaxes the credit constraint of the customer. The customer's subsequent requests to the bank to make payments on its behalf will not be delayed as a result of the customer's credit exposure to the bank.

Exhibit 1 shows, for simplicity, the activity of a payments system in which only two banks participate. The horizontal axis shows payments sent by Bank A and the vertical axis shows payments received by Bank A, and vice versa for Bank B. Two sets of reaction functions are shown. A reaction function shows

EXHIBIT 1
Payments Reaction Curves and Equilibrium



the level of a bank's payments as a function of its expected receipts over some period of time. This function can be represented by the algebraic relationship $P_t^A = a + bR_t^A + \varepsilon_t$, where P_t^A is Bank A's payments in time t , R_t^A represents the receipts of Bank A at time t (both expressed in dollar values), a is the bank's autonomous willingness to send payments (irrespective of its receipts), and the parameter b represents the slope of the reaction function. ε_t is an error term at time t .

The solid-line reaction curves in the exhibit show the banks sending payments without considering their receipts. The reaction curves have a slope of zero with respect to the receipts from their counterparties (in the case of Bank A, its reaction curve is vertical with respect to the horizontal axis, but has a zero slope with respect to its receipts, which are shown on the vertical axis). The intercepts show the autonomous willingness of each bank to make payments and are functions of each

One way that the banking system can coordinate payments and use expected incoming funds as a source of liquidity (in a real-time gross settlement system) in equilibrium is by submitting payments simultaneously, or almost simultaneously.

bank's balances on deposit at the central bank. The equilibrium of payments occurs at the intersection of the two reaction curves, labeled E . In contrast, the dashed-line reaction curves have a positive slope with respect to the receipts from the banks' counterparties, reflecting "strategic complementarity."¹⁴ For these reaction curves, the equilibrium occurs at the point labeled E' . The positively sloped reaction curves—or strategic complementarity—are significant because they show that in equilibrium, the banks can make more payments per dollar of balances. This is the case because at E' , banks conduct more payments starting from the same level of bank deposits at the central bank (the intercepts being the same for both sets of reaction functions). It is in this sense that payments are coordinated in equilibrium. The lower the level of coordination—or the closer the slopes of the reaction curves are to zero—the greater a bank's balances at the central bank must be for that bank to make a given value of payments. (Later in this article, we confirm that the slopes of banks' reaction functions fell significantly in the days after September 11, 2001.)

One way that the banking system can coordinate payments and use expected incoming funds as a source of liquidity (in a real-time gross settlement system) in equilibrium is by submitting payments simultaneously, or almost simultaneously.^{15,16} In the Fedwire funds transfer service, banks typically send the bulk of their daily payments between 3:30 p.m. and 5:30 p.m., and this pattern is very stable. In that way, banks recirculate liquidity very quickly and take advantage of offsetting payments without incurring daylight overdrafts for an extended period of time.

Another strategic element in making payments (in an RTGS system) is the risk to which a bank is subject when paying out funds in advance of receiving funds from a counterparty.¹⁷ A perceived increase in this risk can result in banks delaying the submission of their payments while they await the arrival of payments from counterparties.¹⁸ The actions of a central bank cannot directly reduce this risk, but they can weaken the spillover effect of this risk on banks' willingness to send payments to third-party banks. Under normal circumstances, this risk is relatively low, but in the days following September 11, the risk may have affected banks' willingness to submit payments in a timely manner, notwithstanding the pledge of the Federal Reserve System to provide low-cost liquidity to the banks.

EXAMPLE OF A COORDINATION FAILURE

If a bank fails to make an expected payment, the ability of other banks to make payments can be disrupted in that they send fewer payments, which results in fewer receipts by their counterparties, thus creating a downward cycle.

Consider the following example of three banks, each of which has to pay one of the other banks once during the day. Assume overdrafts are not allowed. Exhibit 2 illustrates the situation. Suppose that under normal circumstances, Bank A pays Bank B every morning. Bank B, using funds transferred from Bank A, pays Bank C; then Bank C can pay Bank A. However, if Bank B fails to pay Bank C, then Bank C cannot pay Bank A. Bank B accumulates deposits at the Federal Reserve as its "due froms" are paid to it by a Fedwire transfer, while Bank A and Bank C together have reduced deposits at the Federal Reserve but have not reduced their "due froms." Thus, the inability of a bank to send out payments causes that bank's deposits to pile up and reduces the ability of other banks to send funds.

One measure of concentration in banks' balances at the central bank is the Herfindahl-Hirschman index (HHI).¹⁹

As shown in Exhibit 2, the concentration level in deposits at the central bank rises considerably when the expected payment from Bank B is not made (from either the opening level of balances or from expected end-of-day balances), leaving Bank A and Bank C unable to make payments.

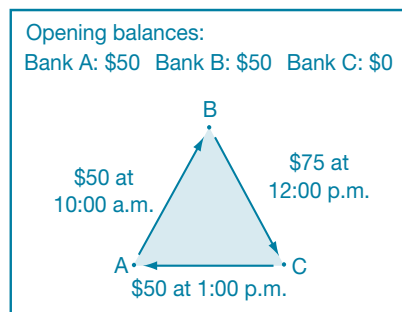
A measure of liquidity usage is provided by the system's *turnover ratio*—the ratio of the value of total payments made to total deposits. In the exhibit, the turnover ratio falls from 1.75 to 0.5. The lower turnover ratio shows that the payments made are more costly in terms of bank balances, which indicates an increase in the demand for liquidity per dollar of payments.

Another measure of liquidity is the *netting ratio*. This is the ratio of the day's total payments to the amount of funds that would need to be transferred between accounts if only the net amounts flowing between banks were exchanged.²⁰ In the exhibit, the netting ratio falls from 7 to 1 as the expected payment—and subsequent payments—fail to be made. The expected level of 7 shows that the banks would only need to hold \$25 (to be held by Bank B) if they were to make all payments simultaneously (or transfer only net amounts) and still comply with the rules that their balances not fall below \$0. The actual level of the netting achieved shows again that the

EXHIBIT 2

Example of the Effects of One Bank's Failure to Send Payments

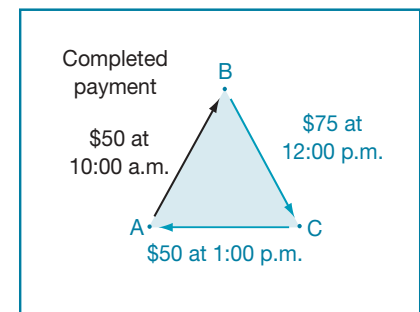
Balances and Expected Payments



Closing balances after payments: Bank A: \$50 Bank B: \$25 Bank C: \$25

Herfindahl-Hirschman index of concentration of opening balances: 5,000; closing: 3,750; turnover ratio: 1.75; netting ratio: 7

Bank B Cannot Send Payment to Bank C



Closing balances after interruption: Bank A: \$0 Bank B: \$100 Bank C: \$0

Herfindahl-Hirschman index of concentration of balances after payment interruption: 10,000; turnover ratio: 0.5; netting ratio: 1

Assets and Liabilities of Banks at Opening of Day and after Bank B Fails to Pay Bank C

	Bank A		Bank B		Bank C	
	Assets	Liabilities	Assets	Liabilities	Assets	Liabilities
Opening	Balances at central bank: \$50 Due from Bank C: \$50 Other	Due to Bank B: \$50 Other	Balances at central bank: \$50 Due from Bank A: \$50 Other	Due to Bank C: \$75 Other	Balances at central bank: \$0 Due from Bank B: \$75 Other	Due to Bank A: \$50 Other
After interruption of payments	Balances at central bank: \$0 Due from Bank C: \$50 Other	Due to Bank B: \$0 Other	Balances at central bank: \$100 Other	Due to Bank C: \$75 Other	Balances at central bank: \$0 Due from Bank B: \$75 Other	Due to Bank A: \$50 Other

actual payments are more costly than expected and—to the extent that banks wish to make payments—indicates that demand for liquidity rises.²¹

Bank C, if it still wishes to make the payment to Bank A (or if there are more “rounds” of payments to be made later in the day, or on the next day), can borrow funds on the interbank market or borrow from some other party, typically the central bank. In addition, the central bank can add reserves to the system through open market operations.

If it were to borrow on the interbank market, from whom would Bank C borrow? Only Bank B has funds to lend. It might be the case that although Bank B cannot feasibly send the expected payment to Bank C, perhaps because communications with its customer are impaired, Bank B is able to lend to Bank C. In this case, there is an increase in demand for borrowing on the interbank market, and Bank B would lend more than usual in that market. The payment by Bank C to Bank A would be accomplished. If Bank B cannot easily make an interbank loan because of technical difficulties, then the central bank can inject reserves either through the discount window or open market operations. In either case, Bank C would make its payment, but, once again, the turnover ratio would fall. In this case, the turnover ratio falls not necessarily because payments values fall, but rather because the amount of reserves in the system needed to accomplish payment has risen.

The example illustrates the fragile nature of using payments coordination as a source of liquidity for banks. One bank’s failure to pay as expected because of a technological problem can be felt as a liquidity shortage by the bank’s counterparties, and their counterparties, making payments activity more costly.

Payments Disruptions Following September 11, 2001

After the attacks on the morning of September 11, it was immediately clear to financial market participants that general operations and communications and computer systems in Lower Manhattan were not functioning well.²² A direct effect of these difficulties was a reduction in the value and volume of transfers on Fedwire on September 11.²³ Although there were major disruptions to markets during that week—the New York Stock Exchange was closed for four days and the commercial paper market was significantly disrupted—it is worth noting that settlements occurred at the major large-value private-sector settlement systems (the Depository Trust & Clearing Corporation and the Clearing House Inter-bank Payments System [CHIPS]) on the eleventh and subsequent days.

Information on aggregate activity for the banking system on September 11 and the days surrounding it is presented in Table 1. The physical disruptions caused by the attacks are evident in the sharp drop in the volume of payments made on Fedwire. Furthermore, one can observe that the volume of payments remained low for the next two days as physical disruptions caused by the attacks continued to affect banks and their customers.

The value of funds sent on September 11 was \$1.2 trillion, about three-fourths of the average for the benchmark period. However, unlike volume, the value of funds sent had returned to normal levels on the twelfth and was then at elevated levels for the next seven business days.

The aggregate balances of the banking system increased starting on September 12 and reached a peak of \$121 billion on September 14. By Friday, September 21, balances returned to normal levels. Although the Federal Reserve System injected funds into the banking system in a number of ways, the pattern of an increase in balances is mainly explained by discount window loans and open market operations. Recall the turnover ratio, which is the ratio of the value of total payments made to total deposits. In our example, the turnover ratio fell as liquidity was not distributed as expected via the payments system. As we see in Table 1, the turnover ratio for Fedwire funds transfers fell from more than 100 before September 11 to only 18 on September 14, indicating a significant increase in the amount of liquidity used to make a dollar’s worth of payment. Once again, by the end of the next week, the turnover ratio was at normal levels.

TABLE 1
Fedwire Funds Transfer Value and Volume,
and Aggregate Opening Balances with the
Federal Reserve: September 10-21, 2001

Date	Volume	Value (Billions of Dollars)	Balance (Billions of Dollars)
September 10	436,312	1,591	13
September 11	249,472	1,216	13
September 12	332,433	1,696	44
September 13	376,937	1,952	104
September 14	423,256	2,009	121
September 17	462,522	2,312	111
September 18	419,126	1,978	46
September 19	401,420	1,836	19
September 20	433,771	1,921	15
September 21	442,293	1,832	13

Source: Federal Reserve Bank of New York.

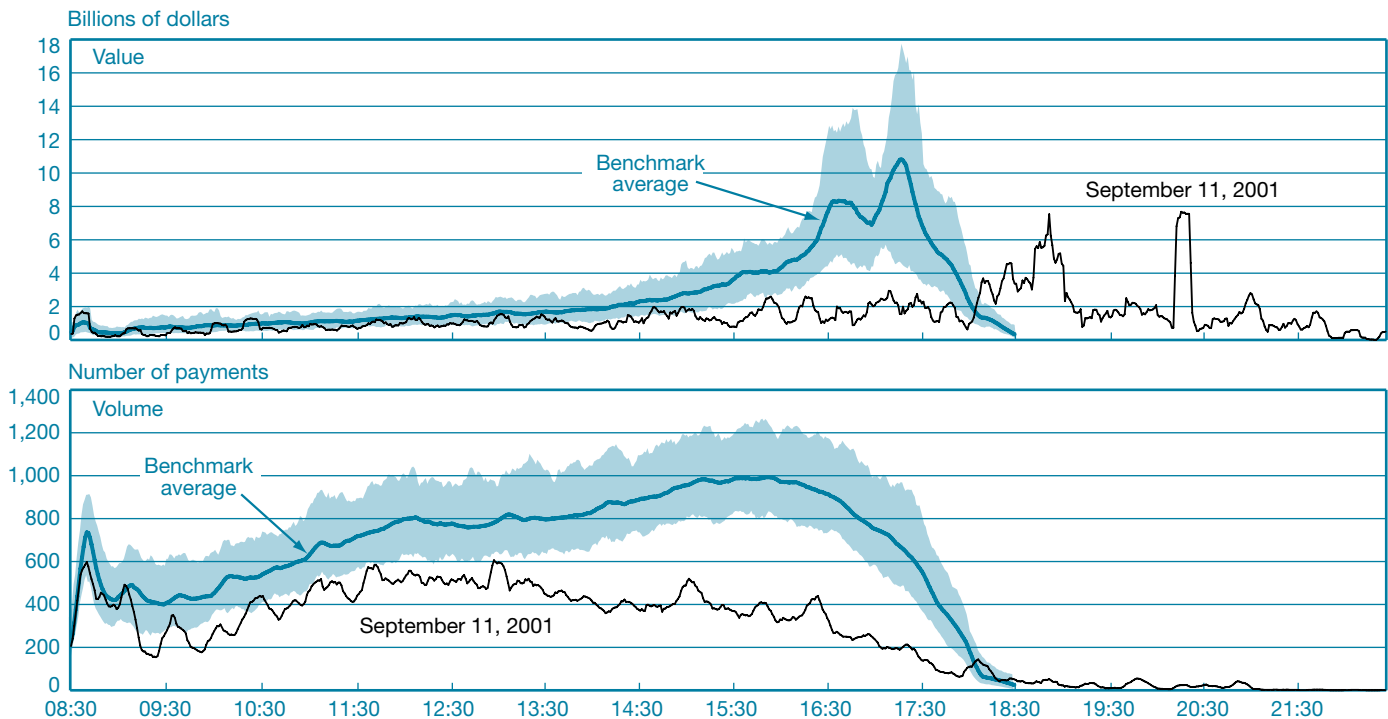
We also examined two alternate estimates of fed funds activity during the period.²⁴ These estimates indicate that some banks were unable to return funds on September 11 that they had borrowed on September 10, presumably because of the physical disruptions following the attacks. Furthermore, because of the physical disruptions, a smaller than average amount of fed funds was sent on September 11. For the next few days, however, fed funds activity was elevated as the Federal Reserve System implemented large open market operations.

Although the values of Fedwire funds transfers and fed funds activity were quickly restored, the timing pattern of these payments was disturbed for a more extended period. As the day of September 11 progressed, it became clear to banks not directly affected by the problems in Lower Manhattan that both the level and timing of activity on Fedwire were significantly affected. Furthermore, banks that were directly affected were

having difficulty sending out payments, communicating with customers, maintaining up-to-date records, and delivering securities.

Chart 1 compares the timing of payments on September 11 with the average for the benchmark period (the benchmark period serves as our measure of normal payments activity and allows us to gauge the effects of the attacks).²⁵ The top panel shows the value transferred per minute and the bottom panel shows the volume of payments transferred per minute. Both panels include a two-standard-deviation band around the benchmark period average to indicate the normal range of variability. As can be seen in Chart 1, another direct effect of the disruptions was a very different pattern of payments timing compared with the benchmark pattern. In particular, more than one-third of the value of payments was sent after the usual closing of Fedwire at 6:30 p.m.

CHART 1
Value and Volume of Funds Sent per Minute
Ten-Minute Moving Average



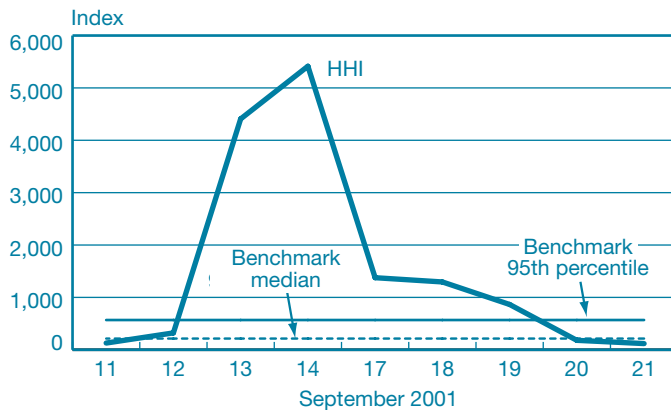
Source: Federal Reserve Bank of New York.

Note: The shaded bands indicate +/- two standard deviations of the benchmark averages.

CONCENTRATION IN BANK BALANCES

Chart 2 shows the median and 95th percentile of the HHI of account balances (for opening balances) in the benchmark data set and for each of nine business days in the attack data set.²⁶ It is clear that the concentration in account balances at the

CHART 2
Herfindahl-Hirschman Index for Start-of-Day
Federal Reserve Balances, by Day



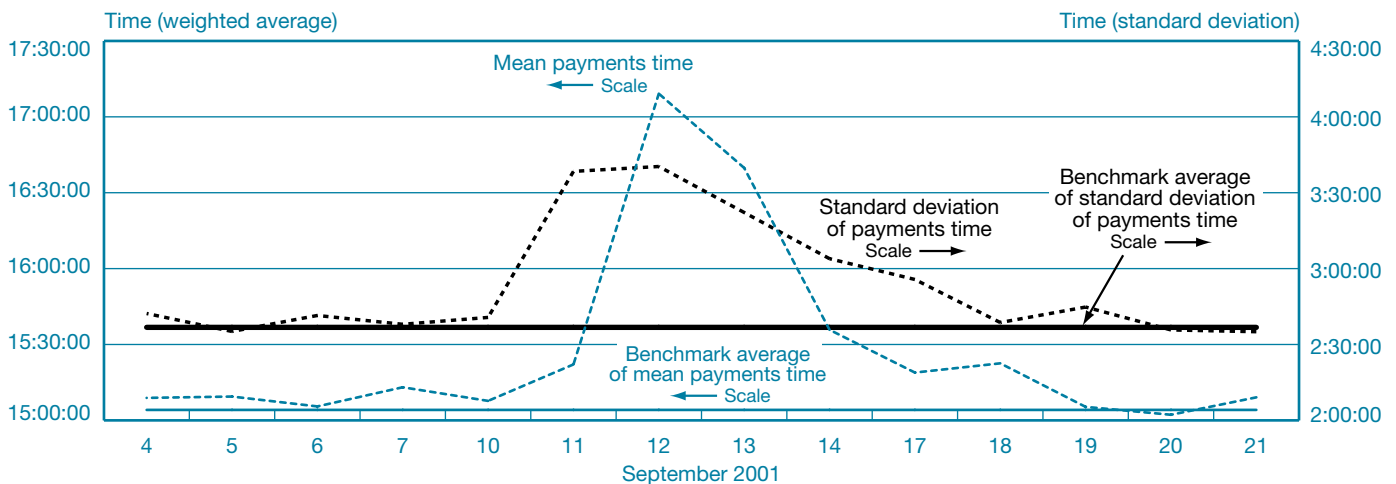
Source: Federal Reserve Bank of New York.

Federal Reserve—rising more than fourteen-fold from its normal levels on the days following the terrorist attacks—was a most unusual event. Furthermore, as we will show, this measure would be even higher if the Federal Reserve had not distributed funds from the discount window in the pattern it did.

MEASURES OF COORDINATION FAILURES

Next, we examine two measures of the tendency of payments activity to be concentrated in a particular time during the day. Chart 3 shows the standard deviation of the timing of payments weighted by their value and the average time of payments, also weighted by value. The standard deviation measure indicates that the variability of payments timing rose precipitously—almost doubling to about four hours from two—indicating an unusual and disordered pattern of timing of payments relative to the benchmark period. In addition, payments were significantly delayed. This is shown by the value-weighted average of the time of payment on Fedwire, which was delayed by approximately two hours relative to its benchmark-period average.²⁷ The same patterns are present in the estimates of fed funds activity as well; the borrowing and

CHART 3
Value-Weighted Average of the Timing of Payments on Fedwire
Benchmark Period and September 4-21, 2001



Source: Federal Reserve Bank of New York.

lending in the banking system's internal market for distributing liquidity occurred later in the day and with a much more varied pattern during the remainder of the week. Both of these changes are highly significant relative to normal patterns.

Another indication of the disorder in payments during those days was the decreased netting ratio of payments. Recall that the netting ratio is the ratio of the day's total payments to the amount of funds that would need to be transferred between accounts if only the net amounts flowing between banks were exchanged. Chart 4 displays a related measure of netting. It shows the amounts of payments in terms of the percentage of the day's total payments offset within each hour of the day. We shaded the area on the chart that represents the mean netting ratio plus or minus two standard deviations for each hour across the 107 days in the benchmark data set. It is clear that the fall in the concentration of payments was accompanied by a drop in the degree to which banks managed to arrange offsetting payments to be made at roughly the same time, particularly in the late afternoon period. Between 3:30 p.m. and 5:30 p.m., banks regularly offset about 20 percent of the day's total payments per hour, and the values transferred per minute are usually the greatest. On the four days immediately following the attacks, offsetting payments made during those two hours fell to between 5 percent and 10 percent of the day's total payments per hour. A day's payments activity averaged \$1.685 trillion in 2001, so a decline of 10 percentage points in offsetting payments during those two hours could result in an increased demand for liquidity of \$163 billion, all else being equal. The coordination of payments timing is crucial in

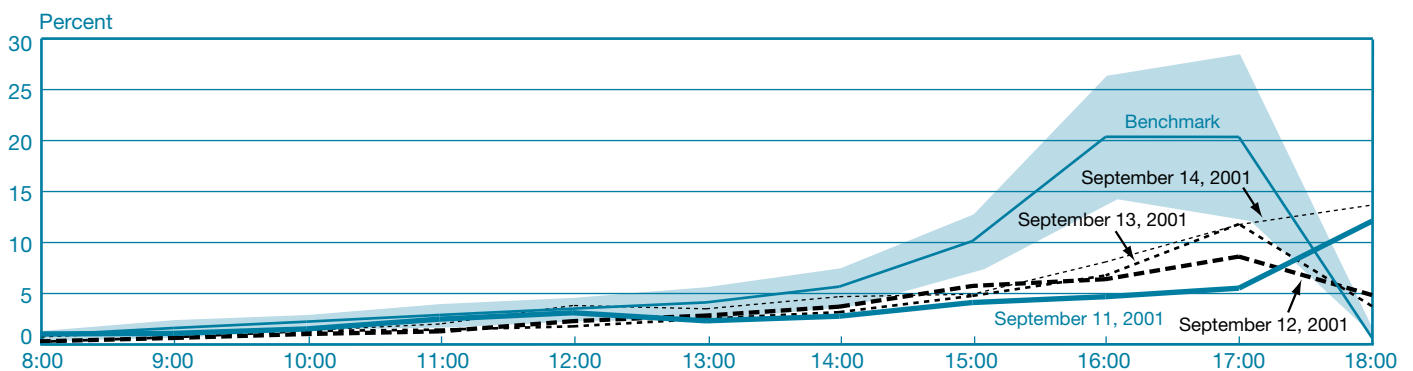
reducing the banks' demand for liquidity. The value of intraday overdrafts on September 11-13 was much higher than usual because fewer offsetting payments were made.²⁸

PAYMENT REACTION FUNCTION ESTIMATES

We estimate the reaction function of bank payments over Fedwire by measuring a bank's own tendency to make outgoing payments as a function of its receipts. In the equation, we posit that a bank's decision to send outgoing payments is dependent on the payments it receives from all other banks, as in the equation we described earlier, $P_t^A = a + bR_t^A + \varepsilon_t$ (this formulation is similar to that of Bech and Garratt [forthcoming], who consider a two-agent game).²⁹ By focusing on the slope coefficient b , we can judge how much strategic complementarity, shown by a positive slope, is present in banks' payments timing strategies.

We estimate the reaction function by pooling the Fedwire activity of twenty large banks—whose payments activity accounts for more than 60 percent of Fedwire volume—together in a panel estimation with fixed effects (Table 2). In this panel approach to estimating the reaction function, a bank's payments in a one-minute interval for each minute during the day are dependent on the bank's receipts in the previous fifteen-minute interval, the bank's opening balance, and the bank's cumulative receipts minus its cumulative

CHART 4
Percentage of the Day's Total Payments Netted during Each Hour



Source: Federal Reserve Bank of New York.

Note: The shaded band indicates +/- two standard deviations of the benchmark averages.

payments sent up to sixteen minutes prior to the minute.³⁰ In addition, we include dummy variables for the time period before 8:30 a.m., for the period between 6:00 p.m. and 6:30 p.m., and for the tenth day of a reserve maintenance period.³¹ We perform another estimation including dummy variables for each half hour of the day between 2:00 p.m. and 6:00 p.m. These latter time-of-day dummies are intended to capture any institutional regularity or very long-run patterns of coordination that are common across banks in their daily payments behavior that might contribute to the pronounced peak in payments in the afternoon (Table 2, panel A). We also include a bank-specific intercept (fixed effect) for each bank in both estimating equations.

The parameters of this equation are estimated under a Tobit assumption for the functional form. That is, we use the same equation, first to predict if a payment would be made in the relevant time interval, and then to predict the payment's size if a payment is to be made. The results from estimating the coefficient on a bank's receipts separately for each of the five days after the attacks are displayed in Table 2. In addition, Table 2 shows the results obtained from pooling the data over the entire benchmark period.³² This coefficient on receipts is a good estimate of the reaction function's slope for large payments, and we label the coefficient estimate the slope. The slope of the reaction function represents a bank's marginal propensity to send out payments in response to the receipt of payments from its counterparties.

For the benchmark period, the slope is positive, as expected, and has a very precisely estimated value of 0.765. This relatively steep slope implies that banks have achieved a high degree of

coordination in their payments activities. At the same time, the steep slope of the reaction function displays strong strategic complementarity among the banks' desired actions, implying potentially large effects of a breakdown in coordination. Adding the time dummies for the afternoon period—to capture institutional or long-run patterns of payments behavior—reduces the size of the coefficient marginally to 0.632 (Table 2).

In contrast, the reaction function slope drops considerably for the first four days after the attacks. The slope is estimated precisely enough for each day that the decline is statistically significant: the estimates on those days are lower than the benchmark estimate. We also estimated the coefficients individually for the five business days before September 11 to assess the variability in the reaction function slope within the benchmark period. Chart 5 plots these results along with the estimates from the nine business days after the attacks. This shows that the average from the benchmark period accurately captures the daily behavior in the days before the attacks. Furthermore, in the week after the attacks, we find that the slope of the reaction function increased above the benchmark level.

The pooling of data across banks assumes symmetry of reaction functions. We also estimated individual bank reaction functions. The results of these estimations are very similar to those of the pooled estimation. The weighted average of the slopes of the reaction is similar in size and follows the same pattern of a sharp dip below the benchmark estimate in the four days following the attacks and a move above the benchmark estimate in the week of September 17. These

TABLE 2
Reaction Function Slopes

	Benchmark	September 11, 2001	September 12, 2001	September 13, 2001	September 14, 2001	September 17, 2001
Panel A: Estimates of the Coefficient on Receipts of the Pooled Model						
Reaction function slope	0.765 (0.0023)	0.229 (0.0528)	0.358 (0.0379)	0.199 (0.0419)	0.599 (0.0394)	1.190 (0.0312)
Panel B: Estimates of the Coefficient on Receipts of the Pooled Model Including Afternoon Time Dummies						
Reaction function slope	0.632 (0.0027)	0.202 (0.0534)	0.249 (0.0389)	0.083 (0.0455)	0.466 (0.0402)	0.863 (0.0343)

Sources: Wholesale Payments Product Office; Federal Reserve Bank of New York Credit Risk Management Function.

Notes: The number of observations is 2,259,920 for the benchmark and 27,920 for each day listed. Standard errors are in parentheses.

individual-bank estimates yield another insight, namely, that the standard deviation of the estimated slope of the reaction function across banks was significantly elevated throughout the period of September 11-14, indicating that banks' actions were highly uncoordinated during that whole period and only began to return to a coordinated set of reactions on September 17.

These results imply that the coordinating equilibrium in the payments flows on Fedwire was greatly disrupted by the events of September 11. In particular, we estimate that the slope of the reaction function fell significantly in the four days immediately after the attacks, indicating that to make a given value of payments, banks held higher balances at the Federal Reserve. This shows the tendency of localized problems in the payments system to spill over to the whole system by the presence of strategic complementarity.

There are at least two interpretations of these results. One is that the increase in the disorder of payments receipts by banks caused a change in the expectations of those banks to receive funds in the normal pattern, and so they experienced an increase in precautionary demands for balances. Consistent with this interpretation, payments activity occurred later in the day and in a more variable pattern than usual, and banks did hold much higher balances. Furthermore, although the communications infrastructure problems were overcome gradually and were largely resolved by Friday the fourteenth, the disorder in payments persisted on Friday and the high balances were observed for several additional days. Another interpretation is that the physical destruction of the communications and business infrastructure made the usual process of payments coordination more difficult—a situation that would

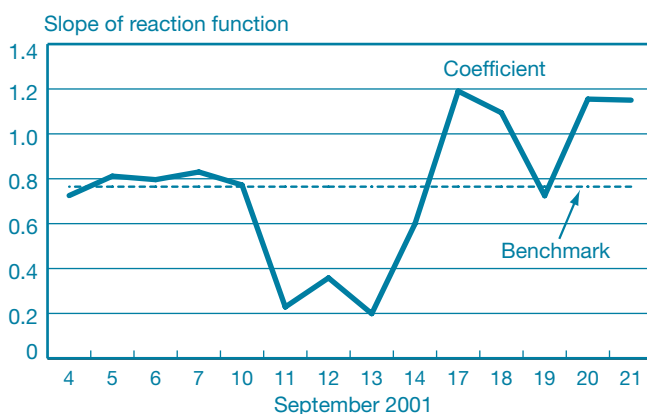
heighten the demand for precautionary balances. For example, if a customer requests a payment to be made on its behalf, but it is at its credit limit, a bank will often check with counterparties to determine if that customer is to receive a payment from a counterparty. In addition, internal communication within the bank takes place among credit officers and payments personnel to ensure that approvals are in place prior to the

[Our results show] the tendency of localized problems in the payments system to spill over to the whole system by the presence of strategic complementarity.

release of a payment. As communication was disrupted generally, these processes occurred more slowly and with greater difficulty. Such obstacles to making payments in a timely fashion would tend to result in a decrease in the slope of the reaction function.

The reaction function estimates for the five business days starting on September 17 indicate that the system quickly managed to regain a coordinating equilibrium. How did the system manage to reestablish the coordinating equilibrium? One direct impetus, of course, was the resolution of technological problems at individual banks.³³ However, this does not necessarily explain the timing of the increase in the reaction function slope estimate, or its higher level (compared with the benchmark) in the week of September 17-21. For a possible explanation of this pattern, we now turn to the actions of the Federal Reserve System.

CHART 5
Slope of Reaction Function of Payments Sent to Payments Received: Fixed-Effects Tobit Model



Source: Federal Reserve Bank of New York.

THE ACTIONS OF THE FEDERAL RESERVE SYSTEM

The Federal Reserve System took a number of steps to address the problems in the payments system after September 11, 2001. Around noon on the eleventh, the Board of Governors of the Federal Reserve System released a statement saying, “the Federal Reserve System is open and operating. The discount window is available to meet liquidity needs.”³⁴ In addition, for the period from Tuesday, September 11, through Friday, September 21, it waived daylight overdraft fees and overnight

overdraft penalties.³⁵ (These actions significantly increased banks' account balances at the Federal Reserve, as shown in Table 1.) Coleman (2002) provides a useful summary of the Federal Reserve's actions for those four days:

“Peak and average daylight overdrafts that depository institutions incurred were approximately 36 and 32 percent higher, respectively, than levels in August 2001” (p. 81).

“Overnight overdrafts increased from an average of \$9 million in August 2001 to more than \$4 billion on September 12 (and the penalty fee was waived on overnight overdrafts). Discount window loans rose from around \$200 million to about \$45 billion on September 12; later, when markets began to function better, Federal Reserve open market operations increased from \$25 billion to nearly \$100 billion” (p. 82).

Federal Reserve staff also contacted banks often during September 11-13, encouraging them to make payments and to consider use of the discount window to cover unexpected shortfalls that the banks might encounter later in the day. The assurance provided by the Federal Reserve's press release and the statements of discount window officials to banks may have prevented a difficult situation from becoming worse.

Once banks' demands for liquidity had been met at low cost and their need to rely on incoming payments had been reduced, banks could once again send payments in more normal patterns. The return to an earlier average payments time on September 14 (Chart 3) indicates that banks were sending payments more freely early in the day compared with the previous two days. Our reaction function slope estimates also point to a return to more strategic complementarity in payments activity on the fourteenth.

In the following week of September 17-21, the Federal Reserve, through open market operations, maintained significant additional liquidity in banks' accounts, with the fed funds rate trading below the target interest rate. During that week, the data suggest that coordination reached higher-than-normal levels, as measured by the steepened slopes of the reaction functions. This is likely a consequence of the low cost of liquidity from overnight balances at the Federal Reserve. Conditions for greater-than-normal flows were present with a low cost of overnight balances, no lingering credit problems at banks, and a backlog of payments at banks to be processed.

Our results, combined with the actions of the Federal Reserve System, can be understood with the assistance of

Chart 6. The upper left panel shows the normal (benchmark period) reaction functions of two representative banks, Bank A and Bank B (using hypothetical data that are consistent with the data and estimates of our model). The intercept of the reaction function represents a bank's autonomous willingness to send payments, even if it receives no payments from other

Once banks' demands for liquidity had been met at low cost and their need to rely on incoming payments had been reduced, banks could once again send payments in more normal patterns.

banks. The intercept also depends on a bank's opening balances. The upward slope of the reaction function is consistent with the strategic complementarity present in the reaction functions we estimated.

The upper left panel shows a second set of reaction functions illustrating the effect of an interruption of Bank B's ability to send payments in response to receiving a payment from Bank A. In this set, Bank B is unable to send out payments until the end of the day. As shown in the chart, Bank B has received many payments, leading to a high balance in its account. Bank A, in contrast, has a low balance and a reduced autonomous willingness to send payments.

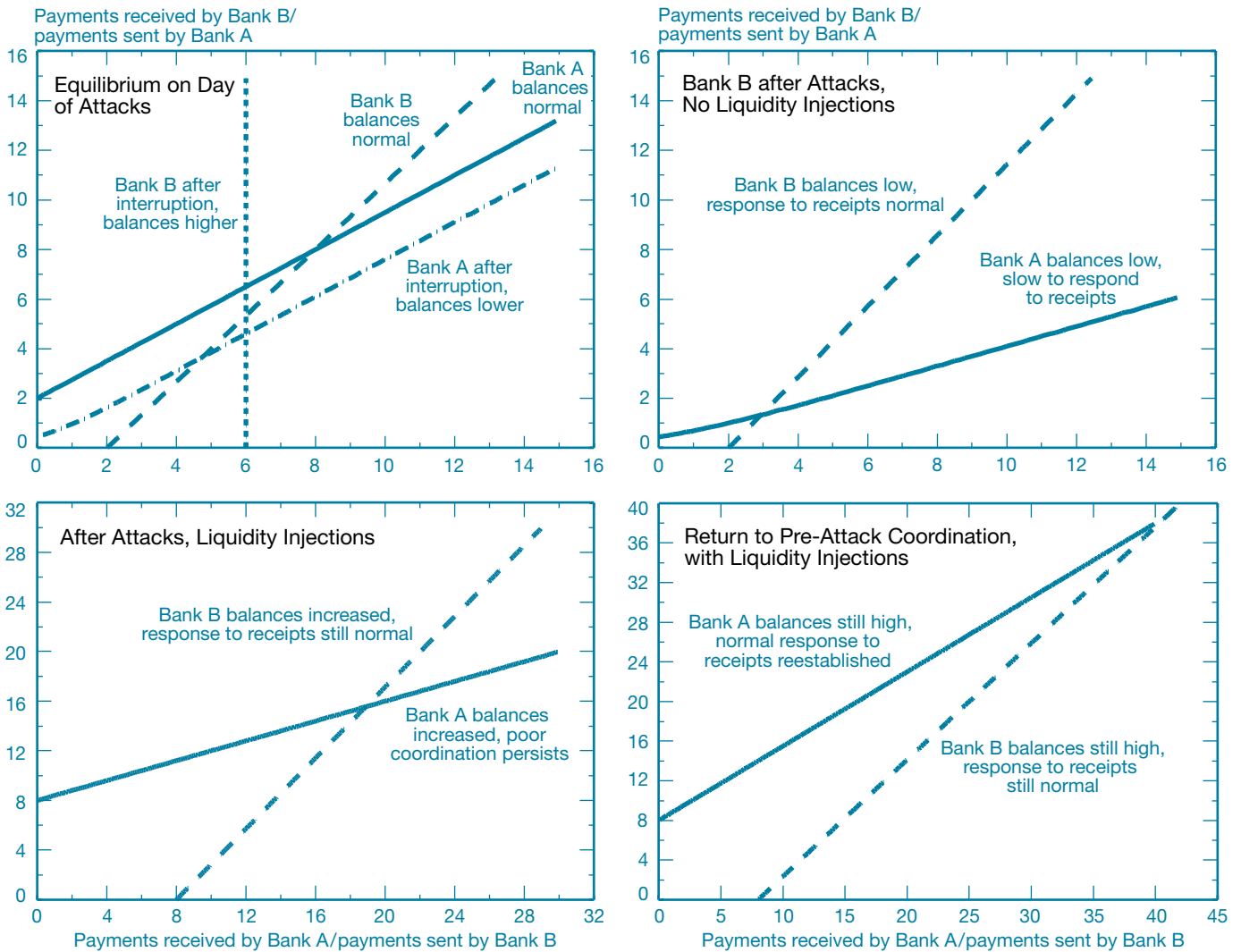
The upper right panel shows the set of reaction functions immediately following Bank B's recovered ability to respond to Bank A. In response to Bank B's previous inability to react to a payment, Bank A has lowered its expectations of receiving further payments. This lowers Bank A's willingness to send out payments in a coordinated fashion. Thus, payments activity is at a low level despite the relatively steep slope of Bank B's reaction function.

The lower left panel shows the effects of liquidity injections by the Federal Reserve System. The increase in balances raises the banks' autonomous willingness to send payments and results in an increase in payments value and in turnover.

Finally, in the lower right panel, the banks' coordination increases further while the liquidity supplied by the Federal Reserve remains in the System. This panel represents the situation during the week of September 17-21. The combined effects led to higher values of payments and payments coordination, as observed in the Fedwire activity that week.

CHART 6

Reaction Functions Illustrating Payments Coordination after the Attacks



Source: Authors' calculations.

DISCUSSION

The Federal Reserve Response

From the point of view of the strategic models of payments timing and submission discussed earlier, the actions of the Federal Reserve System to provide liquidity to the banking system following the attacks of September 11 were appropriate.

The Federal Reserve acted to provide liquidity to banks—liquidity that many banks would have expected to receive under more normal circumstances in the form of incoming payments or via fed funds borrowing.

But precisely how effective were the actions of the Federal Reserve in restarting the coordination of payments activity? That question is difficult to resolve. One way we can try to determine the efficacy of the Federal Reserve's discount window lending is by examining how much less concentrated balances at the Federal Reserve were after discount window

loans were made. We can determine this difference by revisiting the HHI of account balances and comparing it with the concentration of account balances with the discount window loans removed. The discount window loans not only provided a high level of liquidity, but were distributed in such a way as to decrease the concentration of balances. We calculated that the discount window lending led to a distribution of balances across banks that was 8 percent less concentrated (as measured by the HHI) on September 11, and 9 percent less concentrated on the twelfth than the balances would have been if discount window lending had not taken place.

The redistribution of balances and the injection of new balances via the discount window are consistent with the interpretation that the loans allowed banks to carry out payments. By assuring banks that the discount window was available and by waiving daylight overdraft fees, the Federal Reserve's actions tended to eliminate the strategic elements of the timing and submission of payments.

We argue that the Federal Reserve System's actions were likely effective in facilitating payments during the period of technical disruption and in affecting banks' abilities to make and coordinate payments. It is important to note that the

The discount window loans not only provided a high level of liquidity, but were distributed in such a way as to decrease the concentration of balances.

Federal Reserve System's injections of liquidity, and other actions urging banks to make payments, did not resolve the physical problems that banks had in communicating or accessing customer records. Instead, they were aimed at affecting the behavior of banks that were grappling with both the technical difficulties and their resulting liquidity problems.

The Discount Window, Open Market Operations, and the Coordinator of Last Resort

The Federal Reserve System injected liquidity, primarily through open market operations, in the period starting on September 13. On that day, the Federal Reserve advanced

banks a much smaller amount in discount window loans (but still far more than average), and on September 14, its discount window lending was at a normal level. On those same days, the Federal Reserve injected a large amount of liquidity via open market operations.

The switch from primarily using the discount window to relying more on open market operations and the fed funds market occurred after some of the major technical disruptions were resolved, communications improved, and more normal patterns of coordination in payments activity had begun to be reestablished. Without a fully operating fed funds market, open market operations are unlikely to be effective (relative to the use of the discount window) in channeling funds to the institutions that need funds to send payments. Another factor that distinguishes the discount window as a means of injecting liquidity is that it is available to banks upon their request. Under this facility, Federal Reserve Banks may make credit available to depository institutions by providing advances secured by acceptable collateral or by discounting paper that meets the requirements of the Federal Reserve Act (see Board of Governors of the Federal Reserve System [2002] for more discussion of the discount window). In contrast, open market operations are made at the discretion of the central bank, and the liquidity that is injected must typically be redistributed to reach a particular bank's account.

Even when the fed funds infrastructure is fully intact, there are reasons to believe that the interbank market will perform poorly when payments are uncoordinated.³⁶ As we have seen, such situations lead to a generally increased demand for balances. Banks that are reluctant to pay one another are also likely to be reluctant to lend to one another. In these cases, injecting funds through open market operations may not be effective because the funds may not be circulated to the particular banks that most need liquidity. Discount window operations may be more effective in reestablishing coordination, but once coordination has largely been reestablished, open market operations are, in general, preferable because the operation of the fed funds market can be expected to distribute balances in an efficient way.

It is notable that much of the recent literature on the discount window, such as Schwartz (1992), Goodfriend and King (1988), and Furfine (2000), either overlook this motive for the use of the discount window or dismiss it in their evaluations as probably unnecessary (for an alternative view, see Martin [2002]). In all three articles, the authors assume that payments coordination is not an issue. Furthermore, the authors assume that the fed funds market, combined with open market operations, can provide and direct adequate liquidity to

the banking system. Neither of these assumptions is one that can be made for all feasible circumstances.

In general, no single private bank can appropriate all of the spillover public benefit of the coordination, so the incentive to reestablish coordination by borrowing at the target funds rate is likely to be too low relative to the social optimum. Therefore,

Discount window operations may be more effective in reestablishing coordination, but once coordination has largely been reestablished, open market operations are . . . preferable because the operation of the fed funds market can be expected to distribute balances in an efficient way.

the central bank is in a unique position to assist banks in reCOORDINATING payments. That the Federal Reserve waived daylight overdraft fees and penalty fees on overnight overdrafts and assured banks that liquidity was available from the discount window is consistent with providing liquidity at rates that take into account the social benefits of payments coordination. In its role as “coordinator of last resort,” the central bank might use either open market operations to inject funds (as long as the interbank market is functioning well) in sufficient amounts for the interbank rate to trade at a discount to the target rate, or it might use the discount window.

In their September 17, 2001, statement in which they lowered the fed funds target rate and the discount rate, the Federal Open Market Committee (FOMC) and the Federal Reserve Board announced, “the Federal Reserve will continue to supply unusually large volumes of liquidity to the financial markets, as needed, until more normal market functioning is restored. As a consequence, the FOMC recognizes that the actual federal funds rate may be below its target on occasion in these unusual circumstances.”³⁷

Historically, the discount rate has been set below the target funds rate.³⁸ The important point from the coordination-of-payments perspective is that the Federal Reserve can capture some of the public benefit from reestablishing the coordination equilibrium.³⁹ For example, once coordination is reestablished, the number of intraday overdrafts declines, reducing the risk taken on by the Fed.

Payments System Infrastructure and Design

It is worthwhile to ask if central banks could make changes to the operation of payments systems that would prevent or attenuate problems that tend to disrupt the coordination of payments timing. An important change that market participants and financial system regulators are actively pursuing is to work to safeguard the physical infrastructure used in the payments system. The Federal Reserve, along with other financial system regulators, has pursued this approach in the recent “Draft Interagency White Paper on Sound Practices to Strengthen the Resilience of the U.S. Financial System.” In that paper, the regulators identify sound practices to strengthen the U.S. financial system’s resilience. These practices include, among others, a practice for firms that play significant roles in critical markets to “maintain sufficient out-of-region resources to meet recovery and resumption objectives.”

In addition to these fundamental changes in the payments infrastructure, there could also be changes in the protocols for submission and settlement of payments. These changes might occur in ways that would either assist banks in maintaining or reestablishing coordination in the case of an interruption to the normal patterns of payments flows, or might reduce the reliance of banks on payments coordination for liquidity purposes altogether. For example, McAndrews and Rajan (2000) review a number of options to improve the coordination of payments in the normal course of events, such as offering zero-cost overdraft privileges during specified times every day to encourage banks to submit payments during those times. Such an approach might be useful in providing a more targeted focal point to reestablish coordination of payments, but it does not reduce the likelihood of a coordination failure.

Alternatively, the payments system could be designed to eliminate the strategic elements of timing and submission of payments altogether. Several options are possible. One option is to implement new “hybrid” payments systems—an example of which is the new CHIPS system in the United States—that seek to lessen the motive for timing payments to save on liquidity costs.⁴⁰ Pure netting systems accomplish this as well, but at the cost of delays in payments settlement until the designated time and also at the cost of creating intraday credit exposures that remain outstanding until settlement. It is generally agreed that deferred net settlement systems cannot accommodate the requirements of modern financial systems, which require intraday finality of payments, or the settlement of payments throughout the day.

The hybrid payments systems offer an alternative in that they allow for some subset of the payments to be settled during the day, while some other subset remains in a queue of payments awaiting settlement. Various possibilities for settling payments from the queue are possible, but they tend to share a key feature, which is that a bank is strictly better off submitting payments to the queue than delaying a submission until it receives a payment from another bank. Typically, the operator of the payments system can search the queue for offsetting payments. A bank is then better off submitting its payments to the queue because by doing so, the bank makes the settlement of the payment contingent on the receipt of an offsetting payment. Such a system, therefore, offers the possibility that a bank will submit payments to the queue early in the day, letting the operator of the queue management system release that bank's payments when messages of received payments arrive.

It is worth investigating whether such systems, if implemented, would operate well in distributing liquidity and in encouraging the submission of payments, even if one bank were unable to send out payments.^{41, 42} These systems typically have been considered a means for banks to economize on liquidity usage (while achieving intraday settlement of payments) during normal operations. Given the magnitude of the physical disruptions experienced on September 11, 2001, it is now clear that an important consideration in the design of a payments system is how that system would perform under such extreme circumstances.

CONCLUSION

Over the years, the interdependency of payments has become more important and prominent in large U.S. dollar payments for two reasons. First, the turnover on Fedwire has been increasing for years, highlighting the importance of incoming funds as a source of liquidity for payments, and thus creating greater demand for coordination. Second, the level of the concentration of payments has been rising, increasing the ability of the relatively unconcentrated payments providers to coordinate their activities. As coordination has become more important for the normal functioning of the payments system, the breakdown of coordination has become more problematic in that the demands for liquidity balloon as the coordinating equilibrium fails.

In this article, we have shown how the Federal Reserve System acted to restore payments coordination through especially high levels of discount window and intraday lending on September 11 and 12. As communications improved, the Federal Reserve was able to meet more of the market's needs for liquidity through open market operations, allowing the fed funds market to distribute that liquidity. We have also argued that because of the social benefit of reestablishing the payments coordination equilibrium, the injection of funds into the U.S. payments system was important in overcoming the breakdown of the equilibrium in payments coordination. Going forward, it is likely that the discount window will continue to provide an important way for the Federal Reserve to direct liquidity to banks and to improve the coordination of payments in periods of severe disorder in the pattern of those payments.

ENDNOTES

1. Fedwire is a real-time gross settlement (RTGS) payments system. In such systems, payments are executed and finalized very shortly after they are communicated by the originating bank to the system operator and after the system operator communicates the payments details to the receiving bank.
2. See Bank for International Settlements (1997, p. 22) for a similar set of sources of funding. In this article, we refer to “liquidity” as the ability of banks—whose balance sheets often consist of loans and other assets that may be difficult to sell in the short run—to make outgoing payments immediately. As a result, liquidity is a more general concept than “funds in a central bank account.” It includes the expected behavior of other participants in the payments and banking markets, and arises as part of an equilibrium of behavior of the market participants.
3. Service-related balances are primarily made up of required clearing balances, which banks establish to conduct payments operations via Fedwire when their reserve balances are too low to accommodate their payments needs. See Stevens (1993) for a description of required clearing balances.
4. As these values trend upward with growth in economic and financial activity, August 2001 is used as an example of recent activity prior to the period of interest. See Board of Governors of the Federal Reserve System (2001c, p. A5, Table 1.11, lines 22 and 25).
5. An exception to this rule should be noted: required clearing balances earn credits that can be used to offset fees charged by the Federal Reserve System for its priced services. See Stevens (1993) for a more complete discussion.
6. As explained by Furfine (1999), such a large amount of lending is possible, given the much lower balances available to lend, by banks acting as both borrowers and lenders on the same day in the fed funds market on a regular basis.
7. There is a third possibility, previously mentioned: the bank can run an “overnight overdraft” for which it pays a 4-percentage-point penalty above the effective federal funds rate for that day.
8. See Coleman (2002, p. A6, Table 1.12, line 8).
9. See Board of Governors of the Federal Reserve System (2002) for the recent proposal regarding the discount window.
10. See Coleman (2002) for an extensive discussion of the Federal Reserve’s intraday credit policies and operations. Not all banks can borrow intraday from the Fed, and the borrowing of any particular bank is subject to a limit on the amounts that can be borrowed. The Fed guarantees payment of funds transfers across Fedwire, so if a bank has a negative balance in its account and is within its borrowing limit, the Fed transfers the funds to the receiving bank, effectively lending the “daylight overdraft” to the bank that originated the payment.
11. See Coleman (2002, p. 82, Table 8).
12. The turnover ratio has increased in recent decades, both in the United States and abroad. See, for example, Bank for International Settlements (1997).
13. See, for example, Angelini (1998), Bech and Garratt (forthcoming), and Kobayakawa (1997).
14. See Bulow et al. (1985) for a general description of strategic complementarity. Strategic complementarity is indicative of situations in which agents’ payoffs increase with the degree of coordination with other players.
15. Of course, in a deferred (or designated-time) net settlement payments system, offsetting payments made at different times are cumulated and offset at the time designated for settlement. Another way banks can use incoming funds for payments in an RTGS system is by using “throughput guidelines,” which require banks to submit certain percentages of the payments the banks make for the whole day by specified times during the day. Such throughput requirements can regulate the rate of turnover of account balances and are in use in the United Kingdom’s RTGS system, the Clearing House Automated Payments System (CHAPS). Throughput requirements are agreed upon by all system members and therefore might be interpreted as a cooperative means of coordinating payments flows.
16. McAndrews and Rajan (2000) present evidence consistent with this hypothesis for Fedwire payments activity.
17. On this point, see Angelini (2000), Kahn and Roberds (1998), and Kahn, McAndrews, and Roberds (forthcoming).
18. Once again, an equilibrium of payments submissions may result in a delayed (relative to the case in which there is no risk of default by the counterparty), but simultaneous, submission of payments.

ENDNOTES (CONTINUED)

19. The Herfindahl-Hirschman index is the sum of the squares of the market shares of the deposits of the banks. It can vary from 0 to 10,000, with 10,000 indicating that a single bank holds all of the deposits. For example, a level of 5,000 corresponds to a symmetric duopoly in deposit holdings and a level of 3,333 corresponds to a symmetric triopoly.

20. Specifically, the netting ratio over the period from t_1 to t_2 is defined as:

$$N = \left[\frac{\sum_{s=t_1}^{t_2} \sum_i \sum_j P_{ij}^s}{\frac{1}{2} \left\{ \sum_{s=t_1}^{t_2} \sum_i \left| \sum_j P_{ij}^s - \sum_j P_{ji}^s \right| \right\}} \right],$$

where P_{ij}^s represents the value of the payment from bank i to bank j in time period t .

21. The example captures many features of the situation under review. For example, although a bank can generally make a payment if its balance at the Federal Reserve is zero (by borrowing from the Federal Reserve via a daylight overdraft), this is a costly way of making a payment if the bank is expecting other payments to arrive. It is also risky to make a payment by borrowing while awaiting the arrival of other payments because if the other payments were not to arrive, then the bank could incur the substantial penalty of an overnight overdraft. As a result, the failure of an expected payment to arrive can cause another bank to delay sending its payments, which are expected by yet other banks, in turn causing them to delay their payments, and so on. This multiplier effect of the original delay can cause all other banks in the system to demand liquidity.

22. The *Financial Times*, on September 21, 2001, reported that the Bank of New York was the hardest-hit bank because its two principal locations are in Lower Manhattan.

23. Fedwire's operations were uninterrupted on September 11 and thereafter.

24. One of these estimates is gathered by the Markets Group of the Federal Reserve Bank of New York, in its daily survey of fed funds brokers. The other estimate was made by the authors, using a method suggested by Furfine (1999). His method consists of systematically culling all large interbank payments from the records of all Fedwire funds transfers that satisfy certain criteria. Among those criteria are

that the selected payment's values must be at least \$1 million and be made in increments of \$100,000. In addition, each selected payment must match a payment made the following banking day in the reverse direction, and whose value exceeds the selected payment by an amount that would closely correspond to the interest that would be expected given the range of reported fed funds interest rates for that day.

25. The *benchmark* data set includes one day for each ten-day maintenance period from May 1999 to August 2001. In addition, we include the weeks of September 4, 2001, to September 10, 2001, and September 24, 2001, to November 28, 2001, for 107 days in all. The remaining data from September 11, 2001, to September 21, 2001, are used for a detailed analysis of activity on Fedwire on the day of the attacks and the eight business days thereafter.

26. If a large proportion of the balances in the banking system concentrate in one bank's account, then other banks will face, all else being equal, higher costs of making payments, or alternatively may face liquidity constraints on their borrowing, which could preclude their submission of further payments. As shown in Exhibit 2, we use the Herfindahl-Hirschman index to measure concentration of balances in Federal Reserve accounts.

27. Fedwire hours of operation were extended during the first week following the attacks; Fedwire's usual closing is 6:30 p.m.

28. Coleman (2002) reports that daylight overdrafts increased from their August 2001 average of \$32.8 billion to \$45 billion on September 11, \$36 billion on the twelfth, \$41 billion on the thirteenth, and \$54 billion on the fourteenth.

29. Other formulations, more directly comparable with the exact form of the best-reply function of Bech and Garratt (forthcoming), were tested, such as estimating a bank's outgoing payments in response to all other banks' outgoing payments. Similar qualitative results were obtained from those formulations.

30. We estimated this model using receipts both from other banks' funds transfers, as well as the settlement of sales of a bank's government and agency securities, which are also settled via Fedwire. Including these receipts in the estimation had very little effect on the estimates on receipts from other banks' funds transfers and the other variables in the model.

ENDNOTES (CONTINUED)

31. Few banks make payments in the early morning hours. Banks may make “settlement” payments to other banks after 6:00 p.m., but not payments on behalf of customers. Dummy variables for the other days of the reserve maintenance periods were included in other estimations, but were not significant.

32. It should be noted that the results are robust with respect to the exact times over which one measures outgoing payments and receipts.

33. The Bank of New York (2001) issued a press release on September 14 announcing that “virtually all of its systems are up and running.”

34. See Board of Governors of the Federal Reserve System (2001a).

35. The Federal Reserve System announced the waiving of daylight overdraft fees via a Fedwire broadcast message on Friday, September 14.

36. In Europe, where no attacks or technological problems occurred, there was, nonetheless, significantly higher demand for liquidity on September 12, indicated by a spike in interest rates on overnight interbank loans. The European Central Bank supplied an extraordinary amount of liquidity on September 12 and 13. See Bindseil et al. (2002) for a more complete discussion.

37. See Board of Governors of the Federal Reserve System (2001b).

38. See Board of Governors of the Federal Reserve System (2002) for the Board’s May 17 proposal to change discount window lending policies to set the discount rate higher than the target fed funds rate.

39. The public benefit to higher coordination of payments includes the lower cost of payments, as banks can hold lower overnight balances to complete expected payments, which reduces the “inflation tax” to which the public is subject for holding currency or noninterest-bearing balances at the central bank. In addition, banks are subject to either less risk or a shorter duration of risk exposure from their counterparties.

40. McAndrews and Trundle (2001) and Bech and Soramäki (2001) describe various hybrid systems.

41. One area of interesting research would be to examine the performance of CHIPS relative to Fedwire following the terrorist attacks.

42. In the United States, for example, many banks can choose between Fedwire and CHIPS to make payments. A simulation analysis of the effects of infrastructure disruptions in a payments system is presented in Bech and Soramäki (2002).

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