Journal of Monetary Economics 135 (2023) 55–69

Contents lists available at ScienceDirect

Journal of Monetary Economics

journal homepage: www.elsevier.com/locate/jmoneco

Diminishing treasury convenience premiums: Effects of dealers' excess demand and balance sheet constraints☆

Sven Klingler[a,*], Suresh Sundaresan[b]

[a] Department of Finance, BI Norwegian Business School, Nydalsveien 37, NO-0442 Oslo, Norway
[b] Columbia Business School, 1103 Kravis Hall, 665 West 130th Street, New York, NY 10027, United States

ARTICLE INFO

Article history:
Received 27 October 2021
Revised 29 December 2022
Accepted 10 January 2023
Available online 16 January 2023

JEL classification:
D44
D53
G12
G14

Keywords:
Convenience premium
Primary dealers
Risk-free rates
Treasury auctions
OIS

ABSTRACT

After the global financial crisis, the yields of U.S. Treasury bills frequently exceed other risk-free rate benchmarks, thereby pointing to a diminishing convenience premium. Constructing a new measure of dealers' balance sheet constraints for providing intermediation in U.S. Treasury markets, we trace these diminishing convenience premiums to primary dealers' ability to act as intermediaries. Even after accounting for Treasury supply, levels of interest rates, and other controls, falling excess demand of primary dealers in Treasury auctions, their increased Treasury holdings, and balance sheet constraints post-2015, remain key variables in explaining the diminishing convenience premiums.

1. Introduction

As the world's safest and most liquid financial assets, U.S. Treasuries traditionally trade at a "convenience premium" with investors accepting a yield below other proxies of the risk-free rate for the convenience of holding safe and liquid assets. Contrasting with this view, we show that after the global financial crisis of 2008–2009 (a) U.S. Treasury bill yields frequently exceed two benchmarks for the risk-free rate—the maturity-matched overnight index swap (OIS) rate and the yield of Federal Home Loan Bank (FHLB) discount notes—and (b) bill yields exceeding these benchmark rates are a consequence of significant increases in Treasury yields (as opposed to decreasing benchmarks). This observation points to a diminishing convenience premium or an "inconvenience premium" for holding Treasury bills.

☆ We are grateful to Urban Jermann (the editor), an anonymous referee, Patrick Augustin, Darrell Duffie, Claire Yurong Hong, Alexandre Jeanneret, Ritt Keerati, Ben Knox, Arvind Krishnamurthy, Lira Mota, Simon Rottke, Brian Roseman, Amanda Dos Santos, Jesse Schreger, Valeri Sokolovski, Olav Syrstad, Guillaume Vuillemey, conference participants at the European Finance Association, the Southern Finance Association, the SFS Cavalcade Asia Pacific, and seminar participants at BI Oslo, Brandeis University, HEC Montreal, McGill, and University of Münster for helpful comments and suggestions. A preliminary version of this paper was circulated under the title "How Safe are Safe Havens?".

* Corresponding author.
E-mail addresses: sven.klingler@bi.no (S. Klingler), sven.klingler@bi.no, ms122@gsb.columbia.edu (S. Sundaresan).

https://doi.org/10.1016/j.jmoneco.2023.01.002
0304-3932/

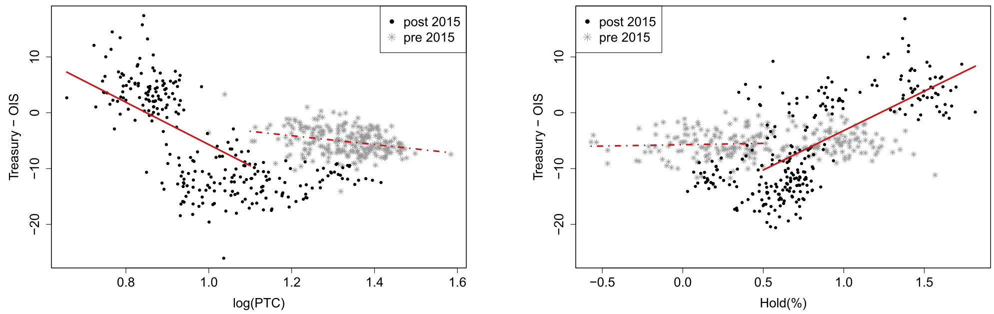

Fig. 1. Treasury-OIS spreads and primary dealer tenders. Panel (a) shows weekly observations of Treasury-OIS spreads, sampled on auction dates, on the y-axis against the logarithm of the primary dealer tender-to-cover ratio on the x-axis. Panel (b) shows weekly observations of Treasury-OIS spreads with 3 months to maturity, sampled on Wednesdays, on the y-axis against relative primary dealer Treasury holdings. The relative Treasury holdings capture the sum of all primary dealer Treasury bill, note, and bond holdings divided by the sum of all outstanding Treasury securities in these categories. The Treasury-OIS spreads are for 3-month Treasury bills against duration-matched OIS rates. The sample period is January 2010 to December 2019 and split into the January 2010 – December 2014 (pre 2015) and the January 2015 – December 2019 (post 2015) periods.

To explain this inconvenience premium, we argue that purchasing and temporarily warehousing large quantities of Treasuries can pose a significant inconvenience for primary dealers, who might face balance sheet constraints, and that their ability to act as intermediaries in Treasury markets has a first-order effect on Treasury yields. To capture this ability, we combine information from Treasury auctions with primary dealer Treasury holdings and construct three closely related variables: (i) Relative primary dealer Treasury holdings, measured as the fraction of outstanding Treasuries held by primary dealers; (ii) primary dealers' excess demand, measured as the quantity of primary dealer bids divided by the total issuance volume in each auction; and (iii) the share of auctioned Treasuries allocated to primary dealers during the previous week.

Fig. 1 illustrates the link between (in)convenience premiums, measured as 3-month Treasury-OIS spreads, on the y axis and either primary dealers' tender-cover ratios or relative Treasury holdings on the x-axis. The introduction of the supplementary leverage ratio (SLR) in 2015, which requires banks to publicly disclose their leverage ratios, tightened banks' balance sheet constraints (e.g., Duffie, 2017, Du et al., 2018b, or Jermann, 2020) and Fig. 1 suggests the impact of our proxies on Treasury yield spreads amplified after 2015. Using regression analysis, we show this link is robust to using monthly or weekly fluctuations in the indicated variables and to controlling for Treasury supply and the level of short rates. We then connect both relative primary dealers' Treasury holdings and excess demand to their share of previously allocated Treasuries in auctions and show that the link between convenience premiums and dealer holdings remains intact when we first project the dealer holdings or excess demand on previous auction allocations. This finding indicates that the allocations affect convenience premiums through dealers' ability to absorb new Treasuries.

Taken together, our results suggest that primary dealers' balance sheet constraints, which can prevent them from absorbing large quantities of Treasury securities, affect even the safest and most liquid assets. In that sense, our results can be seen as precursor to the large drops in Treasury prices during the market turmoil of March 2020, when primary dealers faced large selling pressure in Treasury markets (e.g., Schrimpf et al., 2020, Duffie, 2020 or He et al., 2021).

Summary of main results. To understand why Treasury bill yields are sometimes above other benchmark rates, we start by conducting a simple non-parametric analysis of weekly fluctuations in 1, 3, and 6 month Treasury yield spreads. Focusing first on weeks in which Treasury yields exceed the OIS rate (of matched maturity), we compute the average changes in Treasury-OIS spreads, Treasury yields, benchmark rates, and primary dealer tender-cover ratios in these weeks. We find that the significant increases in Treasury-OIS spreads are accompanied by increases in Treasury yields of virtually identical magnitude while benchmark rates remain stable. In addition, these increases in Treasury yields coincide with significant drops in primary dealer tender-cover ratios and the results remain intact when using alternative benchmark rates or replacing sign changes in yield spreads with abnormal increases (above their 95% quantile). Furthermore, regression analysis confirms that changes in Treasury yields are the predominant driver of short-term Treasury yield spreads. Taken together, these tests suggest that *increases in Treasury yield spreads from negative to positive are driven by increasing Treasury yields and coincide with a lower excess demand by primary dealers in auctions.* We next use regression analysis and find a significant link between Treasury-OIS spreads and primary dealer tender-cover ratios. This association remains intact in different regression specifications, using levels, monthly or weekly changes, and after controlling for other key drivers, such as changes in the volume of Treasury bills outstanding and short-term interest rates. While the supply of Treasury bills loses its explanatory power after controlling for seasonality and changes in the macro-environment (by adding week-of-year and year-month fixed effects), the impact of primary dealers' excess demand on Treasury-OIS spreads remains virtually unchanged. In our analysis of weekly changes, we also instrument primary dealers' excess demand with the previous share of auctioned Treasuries allocated to primary dealers and find that the projected excess demand retains its statistical and economic significance. The idea behind this test is that the previous allocation affects dealers' ability to absorb new Treasuries without directly affecting Treasury yields. In additional robustness checks (reported in the internet appendix), we confirm that all our results are robust to replacing OIS as benchmark rate with FHLB discount note yields.

Focusing next on our new measure for primary dealers' Treasury holdings, we repeat our regression analysis replacing dealers' excess demand with their relative holdings. Consistent with our hypothesis that higher dealer holdings reflect a lower ability to absorb more Treasuries, we find that increases in primary dealers' Treasury holdings correspond to increasing Treasury yield spreads. As before, these results are robust to using different specifications in levels, monthly or weekly changes, and to controlling for Treasury supply and short rates. By instrumenting the relative dealer holdings with the share of auctioned Treasuries allocated to primary dealers, we show that increases in dealer holdings due to higher auction allocations are the main driver of this lower ability. Our findings highlight that primary dealers' balance sheet constraints affect their Treasury intermediation, reinforcing the point made by Duffie (2020): Treasury markets need a "major overhaul" with less reliance on primary dealers' balance sheets.

We next examine how tighter balance sheet constraints affect the link between Treasury yield spreads and either primary dealer' excess demand or relative Treasury holdings. Our hypothesis is that tighter balance sheet constraints make dealers more sensitive to small changes in Treasury yields, strengthening the impact of our primary dealer measures. Motivated by Fig. 1, we first test if the slope coefficient on relative dealer holdings or tender-cover ratios increases after the introduction of the SLR in 2015. Consistent with our hypothesis, tender-cover ratios or relative holdings have a stronger impact on Treasury yield spreads in the post-2015 period; this stronger impact vanishes during the April 2020 to April 2021 period, when regulators temporarily lifted the SLR requirements. In addition, we document a similar effect for two alternative proxies of tighter dealer constraints—quarters during which broker-dealers reduce their book leverage and periods with abnormally high bill trading.

Next, to illustrate how shocks in the primary market transmit to weekly fluctuations in secondary market yields, we first note that Treasury bill auctions are unique as they provide a measure of excess demand every five business days. We use this information to classify auctions as "weak auctions" if primary dealers' excess demand in the auction drops compared to the previous auction and examine Treasury yield spreads in the run up to better and worse auctions. Consistent with Lou et al. (2013), who show that secondary market yields of Treasury notes start increasing several days before a new auction, we find that Treasury bill yield spreads increase in the run-up of an auction. Importantly, for weak auctions, this increase remains statistically significant for five business days, explaining the transmission of demand shocks from the primary market to secondary market yields.

Exploring the fluctuations in Treasury yield spreads around the auction date further, we show that primary dealer excess demand explains the yield changes in the run-up to the auction, even after controlling for proxies of dealer constraints, such as Treasury volatilities and leverage growth. In addition, we highlight a qualitative difference between our results and the analysis of Lou et al. (2013). While the arguments in Lou et al. (2013) suggest a significant drop in Treasury yield spreads after larger auctions (which we also confirm in our data), we argue that Treasury yield spreads *increase* after auctions with higher allocations to primary dealers. This is because higher dealer allocations increase primary dealers' relative Treasury holdings and decrease their excess demand.

Contributions to the Literature. While a large literature emphasizes the convenience benefits of U.S. Treasuries as money-like assets (Longstaff, 2004, Krishnamurthy and Vissing-Jorgensen, 2012, Greenwood et al., 2015, Nagel, 2016, among many others), we document that, in the post-crisis period, the yields of U.S. Treasury bills frequently exceed other risk-free benchmark rates. This observation resonates with Du et al. (2018a), Klingler and Sundaresan (2019), Boyarchenko et al. (2018), Jermann (2020), and Augustin et al. (2020), who examine why the yields of longer-dated Treasuries exceed different benchmarks in the post-crisis period. We contribute to this literature by showing that even short-dated Treasury yields frequently exceed common U.S. benchmark rates and trace this phenomenon to increasing Treasuries yields (as opposed to drops in the benchmark rates).

We link the (in)convenience premiums of U.S. Treasury bills and primary dealers' ability to absorb new Treasuries based on the information obtained from Treasury auctions. As such, our study is related to the literature on price impacts of Treasury auctions (Cammack, 1991, Goldreich, 2007, Lou et al., 2013, Fleming and Liu, 2016, Beetsma et al., 2016 Sigaux, 2017, and Herb, 2018, among others) and studies linking auction information from primary markets to prices in secondary market (Hamao and Jegadeesh, 1998, Pasquariello and Vega, 2009, Beetsma et al., 2018, Gorodnichenko and Ray, 2018, Lengyel and Giuliodori, 2020 among many others). In utilizing the bidding of primary dealers and their relative Treasury holdings, our paper emphasizes the importance of dealers' inventory costs (as studied in Fleming and Rosenberg, 2007) and relates to the large literature examining the impact of financial intermediaries balance sheet constraints on asset prices. Fleckenstein and Longstaff (2019) show that "renting" dealers' balance sheet space is costly and more recently Duffie (2020) and He et al. (2021) show that dealers' constraints were responsible for the Treasury market melt down in March 2020. In addition, tighter balance sheet constraints in the post-crisis period lower the profitability of small arbitrage opportunities (Boyarchenko et al., 2018), make market making in low-risk assets such as Treasuries less profitable (Duffie, 2017), and contribute to a general decrease in dealers' market making activity (Bao et al., 2018, Bessembinder et al., 2018, Dick-Nielsen and Rossi, 2019, among others).

2. Background and stylized facts

In this section, we first provide an overview of the institutional background behind our analysis and then document a set of stylized facts that motivates our study. We examine Treasury bills with the benchmark maturities of 1, 3, and 6-months, which are issued on a regular weekly basis and constitute the safest and most liquid part of the Treasury yield

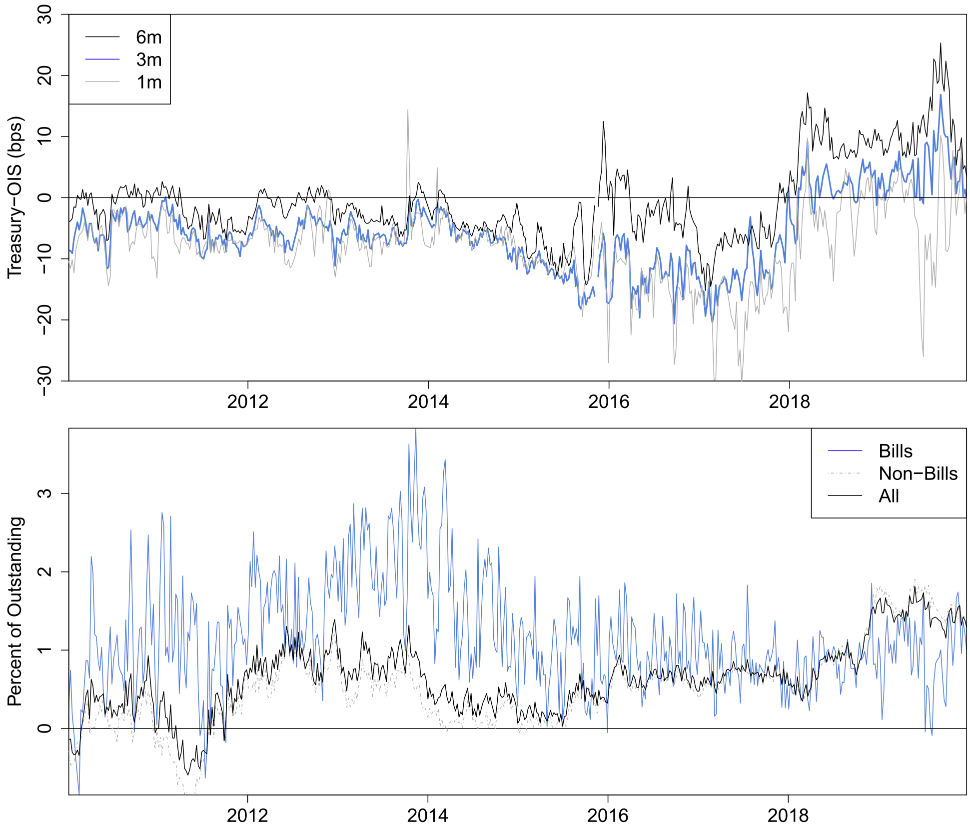

Fig. 2. Treasury-OIS spreads and relative primary dealer Treasury holdings. The top panel shows Treasury-OIS spreads for bills with 1, 3, and 6 months to maturity (sampled on Wednesdays). In the bottom panel, the blue line (grey-dashed line) shows primary dealer Treasury bill (Treasury note and bond) holdings as fraction of all outstanting Treasury bills (Treasury notes and bonds); The black line shows the fraction of all Treasury bills, notes, and bonds held by primary dealers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

curve. Moreover, we focus on the post-crisis period between January 2010 and December 2019 because the granular auction results described below only became available after the financial crisis.[1] Focusing on securities with weekly auctions allows us to capture fluctuations from one auction date to the next instead of transitory price changes around auction dates.

2.1. Treasury yield spreads

To measure the (in)convenience premium in Treasury bills, we use the spreads between the constant maturity Treasury yields (provided in the FED H.15 reports) and two different benchmark rates. Our preferred benchmark rate is the overnight index swap (OIS) rate; the fixed rate swapped against the average FED funds rate (FFR).[2] The top panel of Fig. 2 shows the time series of Treasury-OIS spreads with 1, 3, and 6 months to maturity.

In addition to Treasury-OIS spreads, we use yield spreads relative to the yield of Federal Home Loan Bank (FHLB) discount notes, which are liquidly traded short-term debt issued by FHLBs that are implicitly guaranteed by the U.S. Treasury and enjoys the same tax benefits as Treasury bills. We provide additional plots and summary statistics of these variables in the internet appendix (see Figure A3 and Table A2 in the internet appendix).

2.2. The role of primary dealers

Every week, the U.S. Treasury issues large quantities of, on average, $120 billion Treasury bills,[3] zero-coupon securities with a maturity of one year or less. The largest bidder class in Treasury auctions are primary dealers, which are required

[1] The end date of our study is December 2019 because we circulated the first draft of this paper in March 2020. However, we briefly discuss expanding our sample period to August 2021 in Section 4.

[2] While the FED funds market decreased in size and importance after the financial crisis, the OIS rate remains a popular benchmark rate. Using data from the Depository Trust & Clearing Corporation (DTCC), we estimate that the gross volume of the U.S. OIS market doubled from about $10 trillion in 2012 to $20 trillion in 2018.

[3] We calculate this average number using auction data from TreasuryDirect for the January 2010 to December 2019 period.

Table 1
Auction allocations affect primary dealer holdings and excess demand.

	Relative holdings			Tender-cover ratios	
	(1)	(2)	(3)	(4)	(5)
Intercept	−0.08	−0.01	−0.00	0.04*	0.04*
	(−0.38)	(−0.63)	(−0.08)	(1.77)	(1.79)
$Share_t^{Bills}$	2.19***		0.56***	−0.20***	−0.20***
	(5.33)		(5.01)	(−4.98)	(−4.99)
$Share_{t-1}^{Bills}$	−2.06***		−0.56***	0.13***	0.13***
	(−5.37)		(−5.32)	(3.20)	(3.20)
$Share_t^{NB}$		0.23***	0.20***		−0.01
		(6.94)	(4.59)		(−0.55)
$Share_{t-1}^{NB}$		−0.19***	−0.16***		0.01
		(−5.58)	(−3.96)		(0.63)
Adj. R^2	0.05	0.14	0.10	0.02	0.02
Num. obs.	521	521	521	1,566	1,566

Notes: This table shows the results of regressing changes in relative primary dealer holdings or primary dealers' excess demand for 1, 3, and 6-month bills (measured by the tender-cover ratio), on the indicated shares of primary dealer auction allocations. For relative dealer holdings, we use the sum of all Treasury allocations to primary dealers that occurred between the previous week's Thursday and the current week's Wednesday, divided by the total amount of Treasuries auctioned in the same period. For the excess demand measure, we use Treasury allocations that occured between the previous week's auction date and one day prior to the auction. The numbers in parantheses are heteroskedasticity robust t-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level, respectively.

to participate in every auction and, on average, absorb more than 50% of the auctioned securities. We argue that the ability of primary dealers to act as intermediaries in Treasury markets has a first-order effect on the (in)convenience premium of Treasury bills. To capture this ability, we rely on three closely related variables.

First, we construct a new measure that we label "relative primary dealer holdings" by collecting weekly amounts of Treasuries held by primary dealers and dividing these holdings by the exact amount of Treasuries outstanding at the reporting time (constructed using Treasury auction data). Primary dealers report their Treasury holdings to the Federal Reserve Bank of New York (New York FED) every Wednesday, broken down into Treasury bills and non-bills with different maturities. To eliminate a potential mechanical link between primary dealer Treasury holdings and Treasury debt outstanding, we divide the holdings by the amount of outstanding Treasuries.[4] Second, we obtain a maturity-specific proxy of primary dealers' ability to absorb new Treasuries by dividing the total quantity of primary dealer bids (the primary dealer "tenders") in each auction by the issuance amount (the "cover"). We refer to this measure as tender-cover ratio or excess demand.[5] Third, we construct the share of Treasuries absorbed by primary dealers as weekly sums of all Treasury bill (or non-bill) allocations to primary dealers and divide by the total amount of bills (or non-bills) auctioned in the same period.

The lower panel of Fig. 2 illustrates our new measure of relative bill, non-bill, and total holdings. While the percentage amounts are ranging between −0.5% and 4%, it is important to note that (a) prior to the financial crisis, primary dealers typically held large short positions (e.g., Fleming and Rosenberg, 2007) and (b) that dividing by the total outstanding amounts gives a conservative proxy as primary dealers tend to resell their Treasuries.

To link primary dealer Treasury holdings and auction allocations, we focus on weekly fluctuations in relative holdings, regressing weekly changes in relative holdings on the level of the share of Treasuries absorbed by primary dealers. The idea behind this test is to examine whether auction allocations are a major driver of primary dealers' Treasury holdings and we use the share of Treasuries absorbed by primary dealers between the previous week's Thursday and the current week's Wednesday (when the new dealer holdings are reported). Despite the imperfect timing—the majority of Treasury bill auctions is conducted on Mondays or Tuesdays—Column (1) of Table 1 suggests a strong increase in primary dealer holdings in weeks when the level of primary dealer allocations is high and a subsequent drop the following week.[6] Turning to non-bills, we first note that Treasury auctions in the longer end of the yield curve are less frequent (typically monthly or quarterly), potentially decreasing the importance of auction allocations for weekly Treasury holdings. Despite this potential shortcoming, Column (2) of Table 1 shows a similar pattern as for Treasury bills: Relative non-bill holdings increase in weeks with higher auction allocations and decrease the following week. Finally, we combine bill and non-bill holdings into

[4] Dividing by the total amount of outstanding Treasuries underestimates the fraction of Treasuries held by dealers because primary dealers have two main roles: (i) engage in Treasury auctions and (ii) act as market makers. As off-the-run securities trade infrequently, primary dealer holdings are concentrated in the most recently issued securities and thus dividing by the total amount of Treasuries understates the fraction of Treasuries held by dealers. We explore alternative denominators in the internet appendix (Figure A4 and Table A16).

[5] This ratio differs from the bid-cover ratio, which also includes the bids of other direct and indirect bidders. We show in the internet appendix that it is indeed the primary dealer tender-cover ratio—as opposed to direct or indirect bidders—which is the main driver of Treasury yield spreads.

[6] We summarize the auction information in Figure A2 in the internet appendix and note that 3 and 6-month Treasury bills are typically auctioned on Mondays and in exceptional cases on Tuesdays. By contrast, 1-month bills are typically auctioned on Tuesdays and in exceptional cases on Wednesdays or Thursdays.

one measure and examine how Treasury bill and non-bill auctions affect this aggregate measure. As shown in Column (3), both bill and non-bill allocations are a significant driver which, together, explain 10% of the variation in primary dealers' relative Treasury holdings.

Taken together, these findings are consistent with the narrative that dealers are not buy-and-hold investors but tend to sell the purchased Treasuries after the auction. Moreover, given that most bill auctions are conducted on Mondays or Tuesdays and that longer-dated Treasuries are auctioned less frequently, the fact that the allocation increases relative holdings suggests that primary dealers keep part of the allocated positions on their balance sheet for several days. Hence, higher primary dealer auction allocations can affect yield spreads in secondary markets because they lead to elevated primary dealer Treasury holdings.

Because primary dealers tend to warehouse their allocated Treasury securities for some time after the auction, it is plausible that higher auction allocations also affect primary dealers' excess demand–after receiving a higher allocation, dealers could be less willing to absorb a large quantity of Treasuries in the next auction. To test this assertion, we regress changes in primary dealer tender-cover ratios on auction allocations over the previous week (not including the allocations from the auction day, which would only be available in hindsight). We start by examining the role of Treasury bill allocations. Similar to our previous results for relative holdings, Column (4) shows a mean-reverting pattern where excess demand drops in weeks with higher auction allocations, but increases a week later when inventories revert back. Interestingly, Column (5) shows that non-bill allocations are not significantly connected to primary dealers' excess demand, suggesting that primary dealers' ability to absorb Treasuries in auctions depends mostly on their previous Treasury bill allocations.[7]

We conclude this section by highlighting why excess demand in the form of tender-cover ratios likely affects Treasury yields. First, in contrast to other markets with many small bidders, Hortaçsu et al. (2018) argue that primary dealers are oligopsonistic bidders and adjustments in their individual demand curves can therefore affect Treasury prices. Moreover, while the FED does not explicitly state a "reservation price" for auction participants (as would be the case in, e.g., India, cf Gupta et al., 2021), we note that "the FED will expect a dealer to bid [...] in reasonable price relationship to the range of bidding by other auction participants" (York, 2016). Because yields of close substitutes of the issued securities can be observed in the secondary market, primary dealers cannot place bids for large quantities of Treasuries at unreasonably low prices. Hence, higher quantities bid reflect demand at reasonable prices.

2.3. Stylized facts

To illustrate that Treasury yields and not OIS rates are the main driver of negative Treasury-OIS spreads, we compute the average changes in Treasury bill yields and Treasury-OIS spreads around weeks when Treasury yields exceed OIS rates. For our panel of 1, 3, and 6 month bills in the January 2010 – December 2019 period, we have 65 weeks in which Treasury-OIS spreads increase from negative to positive and the first column in Panel A of Table 2 shows the average changes in Treasury yield spreads, Treasury yields, benchmark rates, and primary dealer tender-cover ratios in these weeks. As we can see from the table, the increases in Treasury-OIS spreads are accompanied by increases in Treasury yields of virtually identical magnitudes but stable benchmark rates. Moreover, these increases in Treasury yields coincide with large and significant drops in tender-cover ratios. As we can see from Columns (2) – (4), a similar pattern emerges when we use FHLB discount note yields instead of OIS as benchmark and when we examine weeks with abnormal increases in Treasury yield spreads, focusing on weeks in which a spread change exceeds the 95% quantile for a given maturity bucket.

Taken together, Panel A of Table 2 suggests that unusual increases in Treasury yield spreads *are entirely driven by increasing Treasury yields and coincide with a lower excess demand by primary dealers in Treasury auctions.* To further motivate our focus on Treasury yields (as opposed to benchmark rates), Panel B of Table 2 confirms that changes in Treasury yields are the main driver of Treasury yield spreads using regression analysis.[8]

3. Primary dealers and treasury yield spreads

In this section, we link Treasury yield spreads and primary dealers' ability to absorb new Treasuries using a regression setting. We first study the effect of primary dealers' auction demand on Treasury yield spreads and focus on the link to relative dealer holdings afterwards. Because weekly Treasury auctions are unique to bills and because primary dealer tenders are only available after the financial crisis, we focus on Treasury bills during the post-crisis period (January 2010 – December 2019).

[7] Additional summary statistics and an overview of all variable descriptions can be found in the internet appendix (Tables A1 and A2).

[8] This is an important difference between Treasury bills and Treasury notes. As shown in Table A3 in the internet appendix, Treasury yields have a substantially lower explanatory power for the spread between Treasury note yields and OIS rates. Hence, in the longer end of the yield curve, Treasury-OIS spreads are not mainly driven by fluctuations in Treasury yields.

Table 2
Stylized facts.

Panel A: Weeks with unusual increases Treasury yield spreads

	Increase −/+		Increase 95%	
	(1)	(2)	(3)	(4)
$\Delta Spread$	4.92***	3.20***	7.70***	7.32***
	(7.51)	(13.22)	(16.50)	(17.36)
$\Delta Treasury$	5.03***	2.43***	7.56***	5.94***
	(6.81)	(7.59)	(9.52)	(8.35)
$\Delta Benchmark$	0.28	-0.77***	0.56	-1.38**
	(0.95)	(-3.06)	(1.09)	(-2.04)
$\Delta\log(PTC)$	-4.51***	-3.24***	-5.72***	-4.84***
	(-4.12)	(-4.02)	(-5.01)	(-3.52)
Benchmark	OIS	FHLB	OIS	FHLB
# Events	65	156	78	71

Panel B: Main drivers of changes in Treasury yield spreads

	OIS as benchmark				FHLB as bemchmark			
	Δy^{Tr}		ΔOIS		Δy^{Tr}		Δy^{FHLB}	
	β	R^2	β	R^2	β	R^2	β	R^2
1m	0.84	0.79	-0.24	0.01	0.70	0.46	-0.55	0.18
3m	0.69	0.69	-0.01	0.00	0.44	0.28	-0.30	0.11
6m	0.54	0.48	-0.13	0.01	0.46	0.26	-0.40	0.17

Notes: Panel A reports averages of weekly changes in Treasury yield spreads, Treasury yields, benchmark rates (using OIS rates or FHLB disount note yields as benchmark), and the logarithm of primary dealer tender-cover ratios (PTC). The weekly changes are from one auction date to the next, focusing on weeks when Treasury yields increase relative to the benchmark rates. In Panels (1) and (2), the events are weeks in which Treasury yields increase above the benchmark rates; in Panels (3) and (4), the events are increases that exceed the 95% quantile of changes during the full sample period. The numbers in paranthesis show t-statistics based on heteroskedasticity-robust standard errors, clustered at the date level. ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively. Panel B shows the β and R^2 from regressions of weekly changes in Treasury-OIS or Treasury-FHLB spreads on changes in Treasury yields or changes in benchmark rates. The sample period in both panels is January 2010 to December 2019.

3.1. Link to primary dealers' excess demand

We now focus on weekly observations of 3 months Treasury-OIS spreads, sampled on auction dates.[9] We start by establishing primary dealers' excess demand as a major driver of Treasury yield spreads. To that end, we run the following regressions:

$$YS_t = \alpha + \beta^{PTC}\log(PTC_t) + \gamma Controls_t + \varepsilon_t. \quad (1)$$

YS_t is the spread between Treasury yield and maturity-matched OIS rate, $\log(PTC_t)$ captures the primary dealer tender-cover ratios, and, in our main specification, we add two variables to $Controls_{i,t}$. First, we include Treasury bill supply ($\log\left(\frac{Bills}{GDP}_t\right)$), which we construct following Greenwood et al. (2015) by using the issuance and maturity information from all Treasury auctions to construct a daily measure of Treasury bills outstanding. Fluctuations in this variable capture how the Treasury auction affects the total supply of Treasury bills and we show later that controlling for more granular supply proxies leaves our results virtually unchanged. Second, we control for the level of the short rate ($Rate_t$) since Nagel (2016) argues that increases in the short rate increase the convenience premium (because the opportunity cost of money increases).

We proceed in six steps. First, we examine the association between the variables in levels. Second, we replace levels with low-frequency changes observed over 4-week periods. Third, we test the link between Treasury-OIS spreads and primary dealer tender-cover ratios using weekly changes. Fourth, we separate the impact of primary dealers' excess demand from changes in Treasury supply by including fixed effects. Fifth, we test if additional controls affect our results. Finally, we use the weekly fluctuations and instrument the tender-cover ratios with previous auction allocations to test our hypothesis that balance sheet limitations affect convenience premiums through primary dealers' excess demand.

We start by examining the link between the level of Treasury-OIS spreads and primary dealer tender-cover ratios. Similar to Krishnamurthy and Vissing-Jorgensen (2012), we estimate ordinary least squares (OLS) regressions in which we incorporate an AR(1) error correction to address the issue of autocorrelation in the error terms. As shown in Column (1) of Table 3, the level of Treasury-OIS spreads is lower when primary dealers' excess demand in auctions is higher.

Second, to get further insights, we follow the procedure outlined by Greenwood et al. (2015) and focus on 4-week changes in the variables. The advantage of focusing on these low-frequency changes is that we capture non-transitory associations between our variables. As using 4-week changes results in overlapping samples, we follow Greenwood et al.

[9] We repeat our analysis for Treasury yield spreads, relative to FHLB discount note yields, and for a panel of Treasury yield spreads with 1, 3, and 6 months to maturity in the internet appendix.

Table 3
Treasury yield spreads and primary dealer bidding.

	Levels	4-week changes	weekly changes			
	(1)	(2)	(3)	(4)	(5)	(6)
log(*PTC*)	−7.07***	−12.01***	−10.76***	−10.47***	−10.57***	−20.81**
	(−3.98)	(−4.08)	(−4.33)	(−3.35)	(−3.75)	(−2.22)
$\log\left(\frac{Bill}{GDP}\right)$	21.76***	21.57***	22.30***	20.90	23.11***	21.45***
	(6.34)	(4.93)	(3.35)	(0.90)	(3.22)	(2.77)
Rate	1.64**	4.26	1.10	−0.82	1.40	0.29
	(2.11)	(0.98)	(0.10)	(−0.08)	(0.13)	(0.07)
Estimation	OLS	OLS	OLS	OLS	OLS	2-SLS
Standard Errors	AR(1)	NW8	Robust	Robust	Robust	Robust
Add. Contr	–	–	–	WOY YM	Iss, Outst, Exc, CDS	–
Adj. R^2	0.54	0.12	0.08	-0.07	0.08	–
Num. obs.	521	521	521	521	502	521

Notes: The dependent variable in this table is the 3-month Treasury OIS spread. Column (1) shows the results of examining levels and assuming that the residuals follow an AR(1) process. Column (2) shows the results using four-week changes. Columns (3) to (6) show the results using weekly changes. The key independent variable is the logarithm of the primary dealer tender-to-cover ration. The other independent variables are the ratio of outstanding Treasury bills to GDP and the level of short rates as proxied by the EFFR. Column (4) shows the results controlling for week-of-year and year-month fixed effects. Column (5) shows the results controlling for the CDS premium on U.S. Treasuries, the amount or Treasuries issued in the current auction, the outstanding amount of Treasuries with the same original maturity, and the difference between the auctioned amount and the estimated amount of public bill holdings maturing (estimated by the Treasury). Column (6) shows the results of a 2-stage least squares using previous auction allocations, aggregated over all Treasury bills, as instrument for the tender-cover ratio (see Column (4) of Table 1 for the first stage). The *t*-statistics are shown in parentheses. For the levels regressions, we compute standard errors assuming that the residuals follow an AR(1) process. For the four-week changes regressions, the *t*-statistics are based on Newey-West standard errors, allowing for a serial correlation up to eight weeks. For the weekly changes we use heteroscedasticity robust *t*-statistics. ***, **, and * indicate significance at a 1%, 5%, and 10% level, respectively. The sample includes all observations for the January 2010 – December 2019 period.

(2015) and adjust the standard errors in this specification using Newey and West (1987) standard errors, allowing for a serial correlation of up to 8 weeks. As shown in Column (2), increases in primary dealers' excess demand correspond to decreasing Treasury-OIS spreads.

Third, focusing on weekly changes in Treasury-OIS spreads, Column (3) of Table 3 confirms the strong link between shocks to primary dealers' excess demand, measured as log-changes in the tender-cover ratio, and changes in Treasury-OIS spreads. To put these results in perspective, we note that the standard deviation of tender-cover ratios in levels, 4-week changes, or weekly changes is 0.21, 0.08, and 0.07, respectively. Hence, a one standard deviation increase in the tender-cover ratio corresponds to a 1.48 basis point higher level of Treasury-OIS spreads, a 0.96 basis point monthly increase, and a 0.75 basis point weekly increase in the yield spreads. In addition, Columns (1) to (3) show that higher Treasury supply has a positive and significant impact on Treasury-OIS spreads while fluctuations in short rates are mostly insignificant.[10]

Fourth, we add fixed effects to distinguish primary dealer tender-cover ratios from changing supply. Because Greenwood et al. (2015) show that the link between Treasury bill yields and bill supply is driven by a strong seasonality in bill supply and Sunderam (2015) argues that year-month dummies can capture unobserved changes in the macro-environment (such as increasing debt levels), we add year-month and calendar-week fixed effects to our analysis. These two fixed effects capture fluctuations in Treasury supply and Column (4) of Table 3 confirms that Treasury bill supply becomes insignificant after adding them as controls. By contrast, the statistical and economic significance of primary dealers' excess demand remains virtually unchanged. Hence, the variation in primary dealers' excess demand explains a part of Treasury-OIS spreads that is distinct from changing Treasury supply.[11]

Fifth, we add changes in the auctioned amount (the cover), the issuance amount in excess of the FED's estimate of maturing bills, our estimated amount of bills in each maturity category outstanding, and the 5-year euro-denominated CDS premium on the U.S. Treasury as control variables.[12] As we can see from Column (5), even after controlling for three additional supply proxies and potential credit risk in U.S. Treasuries, the impact of primary dealers' excess demand on Treasury yield spreads remains virtually unchanged.[13] We omit the coefficient estimates on these variables for brevity and note that

[10] An interesting difference between our results and Nagel (2016) is that changes in the FFR have an insignificant impact on Treasury yield spreads while the supply of Treasuries is significant. This observation resonates with Vandeweyer (2019) who traces the significant post-crisis impact of Treasury supply back to a combination of excess reserves and tight capital constraints. In Section D of the internet appendix, we put our results in perspective to Nagel (2016) and Vandeweyer (2019).

[11] In addition, Table A10 in the internet appendix shows that it is indeed the tenders from primary dealers (as opposed to other auction participants), which drive the results.

[12] The FED provides estimates of maturing securities in each auctioned category and we describe this variable in more detail in the internet appendix. In addition, we use the auction amounts to construct the outstanding amount of all Treasury bills with the same initial maturity as a more granular supply proxy.

[13] When examining tender-cover ratios as auction signals, it is important to note that the covers (i.e. the issuance volumes) are announced several days ahead of the auction and, with the exception of 1-month bills, remain relatively stable over time (see Table A2 in the internet appendix). Hence, it is the

only the CDS premium on U.S. Treasuries has a significant impact. We further examine how credit risk as proxied by CDS in Section E of the internet appendix and find that, during our sample period it manifests mostly in periods around debt ceiling debates.

Finally, we instrument primary dealers' excess demand with previous auction allocations and run a 2-stage least squares (2-SLS) regression, building on the results from Column (4) in Table 1 as first stage and then using the projected tender-cover ratio to explain the Treasury-OIS spread. The idea behind this test is that previous auction allocations affect primary dealers' ability to absorb Treasuries in subsequent auctions. While previous auction allocations affect primary dealers' excess demand, there is no obvious direct link between previous auction allocations and convenience premiums, justifying the exclusion restriction. As shown in Column (6), the projected tender-cover ratio is statistically significant in explaining Treasury-OIS spreads with the correct sign.[14]

3.2. Link to primary dealers' treasury holdings

Proceeding analogously to Section 3.1, we now examine Treasury bill yield spreads sampled every Wednesday and link them to primary dealers' relative Treasury holdings. As before, we focus on Treasury-OIS spreads with 3 months to maturity in the body of the paper and examine the panel of Treasury bills or yield spreads relative to FHLB discount note yields in the internet appendix. To examine the link between Treasury yield spreads and primary dealer holdings, we use regressions of the following form:

$$YS_t = \alpha + \beta^{Hold} Hold(\%)_t + \gamma Controls_t + \varepsilon_t. \tag{2}$$

As before, YS_t is the spread between Treasury yield and maturity-matched OIS rate at time t. The main independent variable is $Hold(\%)$, which can either refer to all primary dealer Treasury holdings relative to the total amount outstanding ($Hold^{All}(\%)$) or to a vector that includes $Hold^{Bill}(\%)$ and $Hold^{NB}(\%)$. As before, $Controls_t$ include Treasury bill supply ($\log\left(\frac{Bills}{GDP}_t\right)$) and the level of short rate ($Rate_t$). Similar to the previous section, we first examine the association between the variables in levels, then study low-frequency 4-week changes, and conclude by examining weekly fluctuations.[15]

Starting with the analysis in levels, Column (1) of Table 4 shows a statistically significant link between the level of all primary dealer Treasury holdings and Treasury-OIS spreads. Column (2) shows that both fluctuations in bill holdings and in non-bill holdings affect the Treasury-OIS spread. Turning to 4-week changes in the variables, Columns (3) and (4) show that the results remain qualitatively similar when focusing on low-frequency changes. While both Treasury supply and the level of short rates become insignificant, primary dealers' Treasury bill holdings and total Treasury holdings remain statistically and economically significant in explaining Treasury yield spreads.

We next focus on weekly fluctuations in Treasury convenience premiums and examine the association with primary dealer holdings using this higher frequency. Such weekly fluctuations are viewed as important indicators of investors' safe asset demand (e.g. Sunderam, 2015 or Kacperczyk et al., 2020) and allow us to study the transmission of demand shocks in weekly Treasury auctions on secondary market yields. Column (5) of Table 4 confirms that increases in total relative dealer holdings coincide with increases in Treasury-OIS spreads on this higher frequency and Column (6) shows that both bill and non-bill holdings affect weekly changes in the Treasury yield spreads.

To put our analysis of weekly fluctuations in perspective with our previous results, we note that the standard deviations of primary dealer Treasury holdings are 0.45 in levels, 0.20 in 4-week changes, and 0.15 in weekly changes. Hence, a one standard deviation increase in relative dealer holdings increases the level of Treasury-OIS spreads by 1.44 basis points, 4-week changes by 0.40 basis points, and weekly changes by 0.48 basis points.

While our results so far point to a positive correlation between Treasury-OIS spreads and primary dealer holdings, we note a potential reverse-causality issue in our analysis so far: Primary dealers might increase their Treasury holdings *because* the bills are relatively cheap (and not vice versa). To mitigate this concern, we build on the results from Table 1 and use the previous auction allocations as instruments for primary dealer holdings. That way, we ensure that the fluctuations in dealer holdings are driven by primary dealers' auction allocations and not by the dealers' decision to invest more in (potentially underpriced) Treasuries. As we can see from Column (7) of Table 4, the projected primary dealer holdings remain statistically significant with the expected sign and a marginally larger regression coefficient compared to the OLS results from column (5).[16]

amount of tenders (which measures demand) that is revealed on the auction day. Column (5) confirms that controlling for the cover leaves the impact of the tender-cover ratio virtually unchanged. In Table A11 in the internet appendix, we further examine how the cover affects the results.

[14] In addition, running some basic diagnostics on our 2-SLS procedure reveals that a weak instrument test returns a p-value below 0.01%, strongly rejecting the null hypothesis of having a weak instrument; a Sargan test returns p-value of 92%, mitigating overidentification concerns; and a Wu-Hausman returns a p-value 29%, suggesting that the 2-SLS estimator is not more consistent than the OLS estimator.

[15] In the internet appendix (Table A17 and A18), we examine if there is link between primary dealer holdings and Treasury turnover. While dealer holdings occasionally coincide with lower Treasury turnover, we find no significant impact of Turnover on yield spreads.

[16] In addition, running some basic diagnostics on our 2-SLS procedure reveals that a weak instrument test returns a p-value below 0.01%, strongly rejecting the null hypothesis of having a weak instrument; a Sargan test returns p-value of 51%, mitigating overidentification concerns; and a Wu-Hausman returns a p-value 34%, suggesting that the 2-SLS estimator is as consistent as the OLS estimator.

Table 4
Treasury bill yield spreads and primary dealer holdings.

	Levels		4-week changes		weekly changes		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$Hold^{All}$ (%)	3.21***		2.04**		3.21***		5.03**
	(4.93)		(2.11)		(4.96)		(2.25)
$Hold^{Bill}$ (%)		0.66***		0.93***		0.59***	
		(3.54)		(3.82)		(3.51)	
$Hold^{NB}$ (%)		2.52***		0.36		2.73***	
		(3.39)		(0.34)		(3.63)	
$\log\left(\frac{Bill}{GDP}\right)$	15.25***	15.09***	4.65	1.97	6.89	6.97	4.83
	(2.89)	(3.03)	(0.89)	(0.38)	(0.93)	(0.95)	(0.65)
Rate	3.45**	4.02***	0.12	0.33	−0.82	−0.76	−0.53
	(2.13)	(2.63)	(0.02)	(0.07)	(−0.15)	(−0.14)	(−0.10)
Estimation	OLS	OLS	OLS	OLS	OLS	OLS	2-SLS
Standard Errors	AR(1)	AR(1)	NW8	NW8	Robust	Robust	Robust
Adj. R^2	0.55	0.57	0.01	0.03	0.04	0.04	–
Num. obs.	514	514	513	513	513	513	513

Notes: The dependent variable in this table is the 3-month Treasury-OIS spread. Columns (1) and (2) show the results of examining levels and assuming that the residuals follow an AR(1) process. Columns (3) and (4) show the results using four-week changes. Columns (5) to (7) show the results using weekly changes. In odd columns, the main independent variable is the total primary dealer Treasury holding, divided by the total amount of Treasuries outstanding. In even columns, the key independent variables are primary dealer holdings of Treasury bills, divided by the total amount of Treasury bills outstanding, and primary dealer holdings of non-bills, divided by the total amount of non-bills outstanding. The other independent variables are the ratio of outstanding Treasury bills to GDP and the level of short rates as proxied by the EFFR. To compute the exact quantities of Treasury debt outstanding, we use the auction schedules provided on www.treasurydirect.gov. The *t*-statistics are shown in parantheses. For the levels regressions, we compute standard errors assuming that the residuals follow an AR(1) process. For the 4-week changes regressions, the *t*-statistcs are based on Newey-West standard errors, allowing for a serial correlation up to eight weeks. For the weekly changes regressions, the *t*-statistcs are based on heteroskedasticity robust standard errors. ***, **, and * indicate significance at a 1%, 5%, and 10% level, respectively. The sample includes all observations for the January 2010 – December 2019 period.

Taken together, Table 4 shows that the cost of temporarily warehousing Treasuries has a direct impact on Treasury yield spreads. This result accords well with Fleckenstein and Longstaff (2019), who show that "renting" primary dealers' balance sheets by trading Treasury note futures instead of physically trading the underlying securities is costly.

4. The role of regulatory constraints

Motivated by Fig. 1, which suggests larger fluctuations in Treasury-OIS spreads in the second half of our sample period, we examine the role of tighter balance sheet constraints. To that end, we focus on January 2015, when it became mandatory for banks to publicly disclose their supplementary leverage ratio (SLR). The SLR is a capital requirement based on banks' total exposure, independent of risk weights, and increases banks' balance sheet costs (e.g. Duffie, 2017 or Du et al., 2018b). The impact on balance sheet costs is especially pronounced for low-risk market making such as purchasing and selling Treasuries. While SLR compliance became mandatory in January 2018, the public disclosure date in January 2015 is key as banks started signaling their ability to comply with the new regulation. Because Treasury markets are reliant on intermediation by primary dealers, a change in their ability to make markets can directly affect Treasury yields.

Consistent with higher balance sheet costs, Table 5 shows that the variance in Treasury yield spreads is significantly higher in the January 2015 to December 2019 period, compared to the January 2010 to December 2014 period. In this context, it is important to note that the elevated variance in Treasury yield spreads is not mirrored by market volatility; the average implied volatility of stock markets as measured by VIX is lower in the January 2015 to December 2019 period. More

Table 5
Increased volatility of Treasury yield spreads.

	Treasury-OIS			Treasury-FHLB		
	σ^{Pre}	σ^{Post}	*p*-value	σ^{Pre}	σ^{Post}	*p*-value
1m	3.10	8.00	0.00	2.71	5.05	0.00
3m	2.30	8.48	0.00	1.91	5.43	0.00
6m	2.44	8.87	0.00	2.33	5.30	0.00

Notes: This table provides a comparison between the variance of the level of Treasury-OIS or Treasury-FHLB spreads during the January 2010 – December 2014 period with the January 2015 – December 2019 period. *p*-value is the *p*-value of an *F*-test of equality in the two variances. The sample period in all three panels is January 2010 to December 2019.

Table 6
The impact of balance sheet constraints.

	$PD = \log(PTC)$			$PD = Hold^{All}(\%)$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
ΔPD	−6.35***	−1.67	−5.69***	1.97***	1.67*	2.36***	1.96***
	(−5.13)	(−1.33)	(−5.36)	(3.02)	(1.76)	(3.72)	(3.48)
$\Delta PD \times \mathbb{1}_{\{t\geq 2015\}}$	−6.35**			6.29**			
	(−2.10)			(2.48)			
$\Delta PD \times \mathbb{1}_{\{t\in(Apr20,Apr21)\}}$	8.08**			−7.20**			
	(2.04)			(−2.00)			
$\Delta PD \times \mathbb{1}(\Delta Leverage < 0)$		−11.47***			2.69**		
		(−4.72)			(2.10)		
$\Delta PD \times \mathbb{1}(Trade \geq q(80\%))$			−21.07***			4.76**	
			(−4.29)			(2.46)	
$\Delta PD \times \mathbb{1}(OTR)$							1.54***
							(2.65)
Add. Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Maturity FE	Yes	Yes	Yes	–	–	–	–
CUSIP FE	–	–	–	–	–	–	Yes
Adj. R^2	0.07	0.09	0.11	0.16	0.06	0.05	0.01
Num. obs.	1,818	1,365	1,563	595	450	513	36,799

Notes: The dependent variable in this table are weekly changes in Treasury-OIS spreads. In Columns (1) to (3) the changes are sampled from auction date to auction date; In Columns (4) to (7) the changes are sampled on Wednesdays. In Columns (1) to (3), we focus on 1, 3, and 6-month on-the-run Treasury yields (data source: FRED). In Columns (4) to (6) we focus on 3-month on-the-run Treasury yields (data source: FRED). In Column (7) we obtain the yields of all Treasury securities with maturity between 2 and 52 weeks from CRSP. *PD* is either the primary dealer tender-cover ratios (Columns (1) to (3)) or the primary dealer relative Treasury holdings (Columns (4) to (7)). $\mathbb{1}_{\{t\geq 2015\}}$ is an indicator variable that equals one from January 2015 on. $\mathbb{1}_{\{t\in(Apr20,Apr21)\}}$ is an indicator variable that equals one during the Apri 2020 to April 2021 period, when the leverage ratio was lifted. $\mathbb{1}(Trade \geq q(80\%))$ is an indicator variable that equals one in weeks when the relative trading volume of Treasury securities (relative to the outstanding volume) exceeds its 80% quantile. $\mathbb{1}(\Delta Leverage < 0)$ is an indicator that equals one in quarters when the book value of broker-dealer leverage decreases. $\mathbb{1}_{\{OTR\}}$ is an indicator variable that equals one if a given Treasury security is currently on-the-run. Add. Controls include changes in the bills-to-GDP ratio and the level of the short rate. The numbers in parentheses are *t*-statistics based on heteroskedasticity robust standard errors, which are clustered at the time level in Columns (4)–(6). ***, **, and * indicate significance at a 1%, 5%, and 10% level respectively. The sample period is January 2010 to December 2019 in Columns (1), (4), and (7), In Columns (1) and (4), we expand the sample period to August 2021 to incorporate the lifting of the leverage ratio. In Columns (3) and (6), the sample ends in September 2018 due to data available for the book value of broker-dealer leverage. Columns (1) to (3) include maturity-fixed effects. Column (7) includes CUSIP-fixed effects.

recently, the importance of the SLR for Treasury markets was confirmed in April 2020 when regulators waived Treasuries from SLR calculations during the COVID-19 market turmoil (see He et al., 2021).

We now test the statistical significance of the patterns illustrated in Fig. 1 focusing on weekly changes in Treasury-OIS spreads. Specifically, we test if Treasury-OIS spreads became more sensitive to primary dealers' excess demand and relative Treasury holdings after the introduction of SLR disclosure requirements in January 2015. We focus on Treasury-OIS spreads instead of Treasury-FHLB spreads because the leverage ratio affects dealers' cost for holding both Treasuries and FHLB discount notes, while OIS are less balance sheet intensive (e.g., He et al., 2021). To explain the elevated volatility of Treasury-OIS spreads, our hypothesis is that higher balance sheet costs amplify the link between primary dealer tender-cover ratios and Treasury yield spreads because primary dealers are more sensitive to small changes in convenience premiums. We use weekly changes in regression specifications (1) and (2), in Table 6 adding a dummy-slope variable that is equal to changes in primary dealers' relative Treasury holdings or excess demand from January 2015 on and zero otherwise. To ensure that it is the introduction of the SLR reporting that affects our findings, we expand our sample period to August 2021. Doing so allows us to incorporate the April 2020 to April 2021 period when U.S. regulators waived the SLR requirements in the wake of the COVID pandemic. We use this expanded sample period to test if the impact of tender-cover ratios (relative dealer holdings) reverts back to pre-2015 levels while the SLR requirements were waived.

Confirming our hypothesis, Columns (1) and (4) show a significant increase in the impact of tender-cover ratios and relative holdings, respectively. In addition, a dummy-slope variable interacting the relative dealer holdings or tender-cover ratios with a dummy variable that equals one during the April 2020 to April 2021 period is statistically significant with the opposite sign to the post-2015 variable.

We next examine how dealer constraints affect the link between Treasury-OIS spreads in three additional tests. First, we examine if deleveraging of financial intermediaries affects the relationship. To that end, we follow Adrian et al. (2014) and use information from the financial accounts of the U.S. to construct changes in the book leverage of broker-dealers.[17] Panel (2) of Table 6 shows that primary dealers' excess demand has a stronger impact in quarters when broker-dealers reduce their

[17] This analysis ends in December 2018 because of a change in the December 2019 version of the flow of funds, which allows for negative book equity of broker dealers.

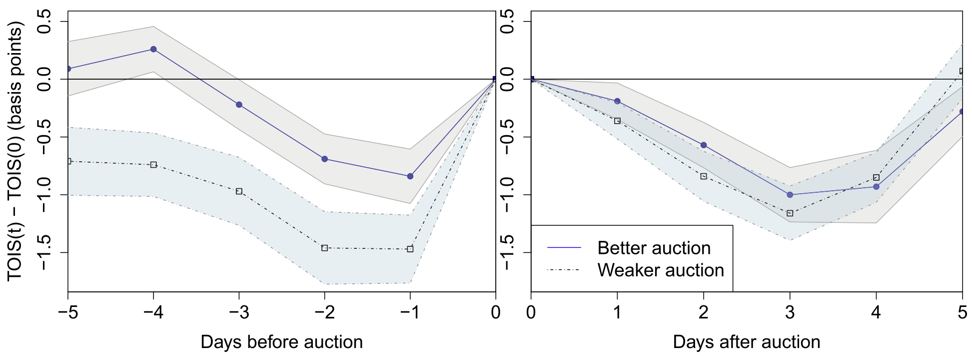

Fig. 3. Changes in Treasury-OIS spreads around auction dates. This figure illustrates average changes in Treasury-OIS spreads with 1, 3, and 6 months to maturity around Treasury auction dates. $t = 0$ corresponds to the auction date and there is an auction, on average, every 5 business days. The shaded interval is the 95% confidence interval, computed using Newey-West standard errors with 12 lags. The left-hand panel compares Treasury-OIS spreads before the auction to the spreads on the auction date. The right-hand panel compares Treasury-OIS spreads after the auction to the spreads on the auction date. The solid line indicates "better auctions" in which the primary dealer tender-cover ratio increased compared to the last auction. The black-dashed line indicates "weaker auctions" in which the primary dealer tender-cover ratio decreased compared to the last auction. The sample period is January 2010 to December 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

leverage, which, according to Adrian et al. (2014), corresponds to tighter dealer constraints. Similarly, Column (5) shows that the impact of primary dealer holdings strengthens during quarters in which primary dealers delever.

Second, as an alternative proxy for elevated costs, we use weeks with abnormally high Treasury trading activity. The idea behind this test is that, in weeks with high trading activity, primary dealers already commit part of their balance sheet to intermediating trades and are therefore less inclined to buy and hold newly-issued securities. To proxy for abnormally high trading activity, we obtain trading volumes of Treasury bills from the New York FED, standardize them with the amount of Treasury bills outstanding, and define weeks with elevated trading activity as weeks where the relative trading activity is above its 80% quantile, measured over the entire sample period. As shown in Column (3), the impact of primary dealer tender-cover ratios strengthens in weeks with high trading activity and Column (6) shows a similar pattern when examining primary dealer holdings.

Finally, we explore the cross-section of *all* Treasuries with maturities between 2 and 52 weeks. To that end, we obtain Treasury yields from CRSP and interpolate the OIS curve to calculate maturity-matched Treasury-OIS spreads. Using this panel of Treasury-OIS spreads, we compute weekly changes, sampled on Wednesdays (to align with changes in dealer holdings). Because primary dealers are most active in the most recently issued Treasury, we expect that fluctuations in their holdings affect the most recently issued securities more than other securities. Column (7) shows that this is indeed the case.

5. Transmission from primary to secondary market

In Section 3.1 we implicitly assume that the excess demand in the primary market affects weekly yield spread fluctuations in the secondary market. However, while there is an almost mechanical relationship between primary dealers' excess demand and the auction high yield, the impact on weekly changes in secondary market yields is less obvious. To connect weekly changes in secondary market yields to auction demand, we build on the findings by Lou et al. (2013), who show that (secondary market) Treasury yields exhibit a "tent-shaped" pattern around auctions—secondary market yields start increasing several days before a new auction, peak on the auction day, and decrease afterwards. While Lou et al. (2013) focus on Treasury notes, we now document a similar pattern for Treasury bills. In addition to Lou et al. (2013), we show that the auction tent is more pronounced when primary dealers' excess demand decreases. This impact of primary dealers' excess demand on the auction tent explains the transmission from primary to secondary markets because Treasury bills are auctioned, on average, every 5 business days.

To analyze the auction tent for Treasury bills, we first compute the difference between Treasury-OIS spreads on auction days and several days before and after the auction.[18] We then compute averages and confidence bands across all 1, 3, and 6 month Treasury bills. To link the auction tent to primary dealers' excess demand, we split the sample into "better auctions", in which primary dealer tender-cover ratios increase compared to the previous auction, and "weak auctions", in which tender-cover ratios decrease compared to the previous auction. Fig. 3 shows the resulting estimates. Because Treasury bills are issued every 5 business days, we split the tent in changes from the previous to the current auction date (left-hand panel) and changes from the current auction to the next (right-hand panel). The difference between Lou et al. (2013) and our analysis is that Treasury bill auctions occur every five business days while the Treasury note auctions studies in Lou

[18] The results remain virtually unchanged when examining Treasury yields instead of Treasury-OIS spreads. The advantage of using Treasury-OIS spreads is that the profits are unaffected by rate change expectations.

Table 7
Auction effects.

Panel A: Analysis of changes around auction dates.

	$TOIS_{t-5} - TOIS_t$		$TOIS_{t+5} - TOIS_t$	
	(1)	(2)	(3)	(4)
log(PTC)	−1.32**	−2.16***	−0.44	−1.10*
	(−2.04)	(−3.31)	(−1.11)	(−1.79)
Treasury IV		−0.08		0.17
		(−0.79)		(1.37)
BD Lev Growth		−0.58**		−0.46*
		(−2.37)		(−1.91)
VIX		0.03		−0.01
		(1.48)		(−0.33)
Adj. R^2	0.01	0.02	−0.00	0.00
Num. obs.	507	445	507	445

Panel B: Analysis of daily changes.

	(1)	(2)
$Offered(t-5, t-1)$	−0.29***	
	(−3.59)	
$Allocated(t-5, t-1)$		0.60**
		(2.23)
Adj. R^2	0.00	0.00
Num. obs.	2478	2478

Notes: This table presents the effect of auction outcomes on Treasury yield spreads. The dependent variable in Panel A captures fluctuations in 3-month Treasury-OIS spreads and is either the difference in Treasury-OIS spreads 5 business days before the auction minus the spread on the auction date (Columns (1) and (2)) or the difference in Treasury-OIS spreads 5 business days after the auction minus the spread on the auction date (Columns (3) and (4)). log(PTC) is the logarithm of the primary dealer tender-cover ratio, *Treasury IV* is the implied volatility captured by the Treasury VIX, *BD Lev Growth* is the aggregate leverage growth of broker dealers, and *VIX* is the implied volatility of S&P index options. The dependent variable in Panel B is the daily change in 3-month Treasury-OIS spreads. $Offered(t-5, t-1)$ is the total amount of Treasury bills auctioned in the five business days prior to the auction. $Allocated(t-5, t-1)$ is the fraction of Treasury bills auctioned in the five business days prior to the auction that were allocated to primary dealers. The t-statistics are shown in parentheses and based on Newey-West standard errors adjusted with 12 lags. ***, **, and * indicate significance at a 1%, 5%, and 10% level, respectively. The sample includes all observations for the January 2010 – December 2019 period. In Columns (2) and (4) of Panel A, the sample ends in December 2018 due to the availability of BD Lev Growth.

et al. (2013) occur less frequently (at a monthly or quarterly frequency). Hence, the "tent" in Treasury bill yields is only comparable to Treasury notes for the 1–2 days before and after the bill auction.

Fig. 3 corroborates the findings of Lou et al. (2013), illustrating a tent-shaped pattern for Treasury bills that starts two days before the auction and ends approximately two days after. Unlike Lou et al. (2013), the tent diminishes over 5 business days due to the higher frequency of bill auctions—after 5 business days the following auction affects the yields. Importantly, even though the auction tent diminishes over 5 days, Fig. 3 shows that $TOIS_{i,t-5} - TOIS_{i,t}$ is significantly lower in weak auctions, that is when primary dealers' excess demand drops. Hence, Fig. 3 shows that the auction tent for bills is more pronounced in weaker auctions, which explains the transmission from primary to secondary markets and illustrates the importance of using weekly auction data.

5.1. Analysis of treasury yield spreads around auction dates

We now examine the role of auction outcomes more formally and distinguish our measure of excess demand in auctions from other measures of primary dealer constraints that were used in previous studies. Specifically, we focus on 3-month Treasury-OIS spreads and separately examine the left ($YS_t - YS_{t-5}$) and right ($YS_t - YS_{t+5}$) part of the auction tents. Columns (1) and (3) corroborate the results from Fig. 3, suggesting that higher tender-cover ratios correspond to significantly smaller increases in Treasury-OIS spreads in the run-up of the auction but to insignificant changes after the auction. To test the robustness of this result to previously established measures of primary dealer constraints, we follow Lou et al. (2013) and control for the implied volatility of Treasury bills (as captured by the Treasury VIX), broker-dealer leverage growth (as estimated by Adrian et al., 2014), and the implied volatility of S&P index options measured by VIX. As shown in Columns (2) and (4), controlling for these variables leads to a small increase in the statistical and economic significance of primary dealer tender-cover ratios. Hence, tender cover ratios captures a part of dealers' ability to absorb new Treasuries not captured by previously established proxies.

To conclude, we highlight a qualitative difference between our results and the analysis of Lou et al. (2013). Lou et al. (2013) argue that larger Treasury auctions predict higher Treasury returns (in our context lower Treasury yield spreads) because Treasury markets slowly recover from the effect of the Treasury auction. Using daily changes in Treasury-OIS spreads, Column (1) in Panel B of Table 7 replicates this result. A higher aggregate amount in Treasury bills auctioned over the 5 preceding business days predicts a decrease in Treasury yield spreads. However, when primary dealers absorb a larger fraction of the auctioned securities, our results from Section 2 suggest that their excess demand drops and their relative Treasury holdings increase. Hence, a higher fraction of Treasuries allocated to dealers should increase the Treasury-OIS spread. Column (2) in Panel B suggests that this is indeed the case.

6. Conclusion

Our findings point to a diminishing convenience premium of U.S. Treasury bills after the financial crisis; Treasury yields regularly exceed the rate in corresponding OIS or the yields of FHLB discount notes. Our results suggest a connection between the (in)convenience premium associated with Treasury bills and primary dealers' ability or willingness to act as intermediaries in Treasury markets. Both our new measure of relative primary dealer holdings and primary dealers' excess demand in Treasury auctions explains a part of the convenience premium unrelated to previously established supply measures.

The results in our paper suggest that even the safest and most liquid assets can be affected by primary dealers' balance sheet constraints, which can prevent them from absorbing large quantities of Treasury securities. In that sense, our results can be seen as a precursor the large drops in Treasury prices during the market turmoil of March 2020, when primary dealers faced large selling pressure in Treasury markets (e.g. Duffie, 2020 or He et al., 2021). Our findings corroborate the view expressed in Duffie (2020) that the combination of tighter balance sheet constraints and large quantities of Treasury securities to intermediate is problematic.

Data availability

Data will be made available on request.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jmoneco.2023.01.002.

References

Adrian, T., Etula, E., Muir, T., 2014. Financial intermediaries and the cross-section of asset returns. J. Finance 69 (6), 2557–2596.
Augustin, P., Chernov, M., Schmid, L., Song, D., 2020. Benchmark interest rates when the government is risky. J. Financ. Econ.. forthcoming
Bao, J., O'Hara, M., Zhou, X.A., 2018. The Volcker Rule and corporate bond market making in times of stress. J. Financ. Econ. 130 (1), 95–113.
Beetsma, R., Giuliodori, M., De Jong, F., Widijanto, D., 2016. Price effects of sovereign debt auctions in the euro-zone: the role of the crisis. J. Financ. Intermed. 25, 30–53. doi:10.1016/j.jfi.2014.11.004.
Beetsma, R., Giuliodori, M., Hanson, J., de Jong, F., 2018. Bid-to-cover and yield changes around public debt auctions in the euro area. J. Bank. Finance 87, 118–134. doi:10.1016/j.jbankfin.2017.10.006.
Bessembinder, H., Jacobsen, S., Maxwell, W., Venkataraman, K., 2018. Capital commitment and illiquidity in corporate bonds. J. Finance 73 (4), 1615–1661.
Boyarchenko, N., Eisenbach, T. M., Gupta, P., Shachar, O., Van Tassel, P., 2018. Bank-Intermediated Arbitrage. Working paper. Federal Reserve Bank of New York. 10.2139/ssrn.3200041.
Cammack, E.B., 1991. Evidence on bidding strategies and the information in treasury bill auctions. J. Polit. Economy 99 (1), 100–130.
Dick-Nielsen, J., Rossi, M., 2019. The cost of immediacy for corporate bonds. Rev. Financ. Stud. 32 (1), 1–41.
Du, W., Im, J., Schreger, J., 2018. The U.S. treasury premium. J. Int. Econ. 112, 167–181. doi:10.1016/j.jinteco.2018.01.001.
Du, W., Tepper, A., Verdelhan, A., 2018. Deviations from covered interest rate parity. J. Finance 73 (3), 915–957. doi:10.1111/jofi.12620.
Duffie, D., 2017. Financial regulatory reform after the crisis: an assessment. Manage. Sci. 64 (10), 4835–4857. doi:10.1287/mnsc.2017.2768.
Duffie, D., 2020. Still the World's Safe Haven? Redesigning the US Treasury Market After the COVID-19 Crisis. Hutchins Center Working Paper 62.
Federal Reserve Bank of New York, 2016. Administration of Relationships with Primary Dealer. Technical Report. Federal Reserve Bank of New York. http://www.newyorkfed.org/markets/pridealers_policies.html.
Fleckenstein, M., Longstaff, F.A., 2019. Renting balance sheet space: intermediary balance sheet rental costs and the valuation of derivatives. Rev. Financ. Stud.
Fleming, M.J., Liu, W., 2016. Intraday Pricing and Liquidity Effects of US Treasury Auctions. Working paper. Federal Reserve Bank of New York.
Fleming, M.J., Rosenberg, J.V., 2007. How do Treasury Dealers Manage their Positions? Working paper. Federal Reserve Bank of New York doi:10.2139/ssrn.972367.
Goldreich, D., 2007. Underpricing in discriminatory and uniform-price treasury auctions. J. Financ. Quant. Anal. 42 (2), 443–466.
Gorodnichenko, Y., Ray, W., 2018. Unbundling Quantitative Easing: Taking a Cue from Treasury Auctions. Working paper. UC Berkeley.
Greenwood, R., Hanson, S.G., Stein, J.C., 2015. A comparative-advantage approach to government debt maturity. J. Finance 70 (4), 1683–1722. doi:10.1111/jofi.12253.
Gupta, S., Sundaram, R.K., Sundaresan, S., 2021. Underwriting government debt auctions: auction choice and information production. Manage. Sci. 67 (5), 3127–3149.
Hamao, Y., Jegadeesh, N., 1998. An analysis of bidding in the Japanese government bond auctions. J. Finance 53 (2), 755–772.
He, Z., Nagel, S., Song, Z., 2021. Treasury inconvenience yields during the Covid-19 crisis. J. Financ. Econ.. forthcoming
Herb, P., 2018. Are US Treasury Auctions Twice Underpriced? Working paper. Northern Arizona University.
Hortaçsu, A., Kastl, J., Zhang, A., 2018. Bid shading and bidder surplus in the us treasury auction system. Am. Econ. Rev. 108 (1), 147–169.
Jermann, U., 2020. Negative swap spreads and limited arbitrage. Rev. Financ. Stud. 33 (1), 212–238.
Kacperczyk, M.T., Perignon, C., Vuillemey, G., 2020. The private production of safe assets. J. Finance. forthcoming
Klingler, S., Sundaresan, S., 2019. An explanation of negative swap spreads: demand for duration from underfunded pension plans. J. Finance 74 (2), 675–710. doi:10.1111/jofi.12750.
Krishnamurthy, A., Vissing-Jorgensen, A., 2012. The aggregate demand for treasury debt. J. Polit. Economy 120 (2), 233–267.
Lengyel, A., Giuliodori, M., 2020. Demand Shocks for Public Debt in the Eurozone. Working Paper. De Nederlandsche Bank.
Longstaff, F.A., 2004. The flight-to-liquidity premium in US treasury bond prices. J. Bus. 77 (3), 511–526. doi:10.1002/lary.24520.

Lou, D., Yan, H., Zhang, J., 2013. Anticipated and repeated shocks in liquid markets. Rev. Financ. Stud. 26 (8), 1890–1912. doi:10.1093/rfs/hht034.
Nagel, S., 2016. The liquidity premium of near-money assets. Q. J. Econ. (December) 1927–1971. doi:10.1093/qje/qjw028.Advance.
Newey, W., West, K., 1987. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica 55 (3), 703–708.
Pasquariello, P., Vega, C., 2009. The on-the-run liquidity phenomenon. J. Financ. Econ. 92 (1), 1–24.
Schrimpf, A., Shin, H.S., Sushko, V., 2020. Leverage and margin spirals in fixed income markets during the Covid-19 crisis. BIS Bull..
Sigaux, J.-D., 2017. Trading Ahead of Treasury Auctions. Working paper. European Central Bank.
Sunderam, A., 2015. Money creation and the shadow banking system. Rev. Financ. Stud. 28 (4), 939–977. doi:10.1093/rfs/hhu083.
Vandeweyer, Q., 2019. Treasury Debt and the Pricing of Short-Term Assets. Working paper. University of Chicago Booth.